

THE DAWN OF HIGH ENERGY NEUTRINO ASTRONOMY

16.03.2022

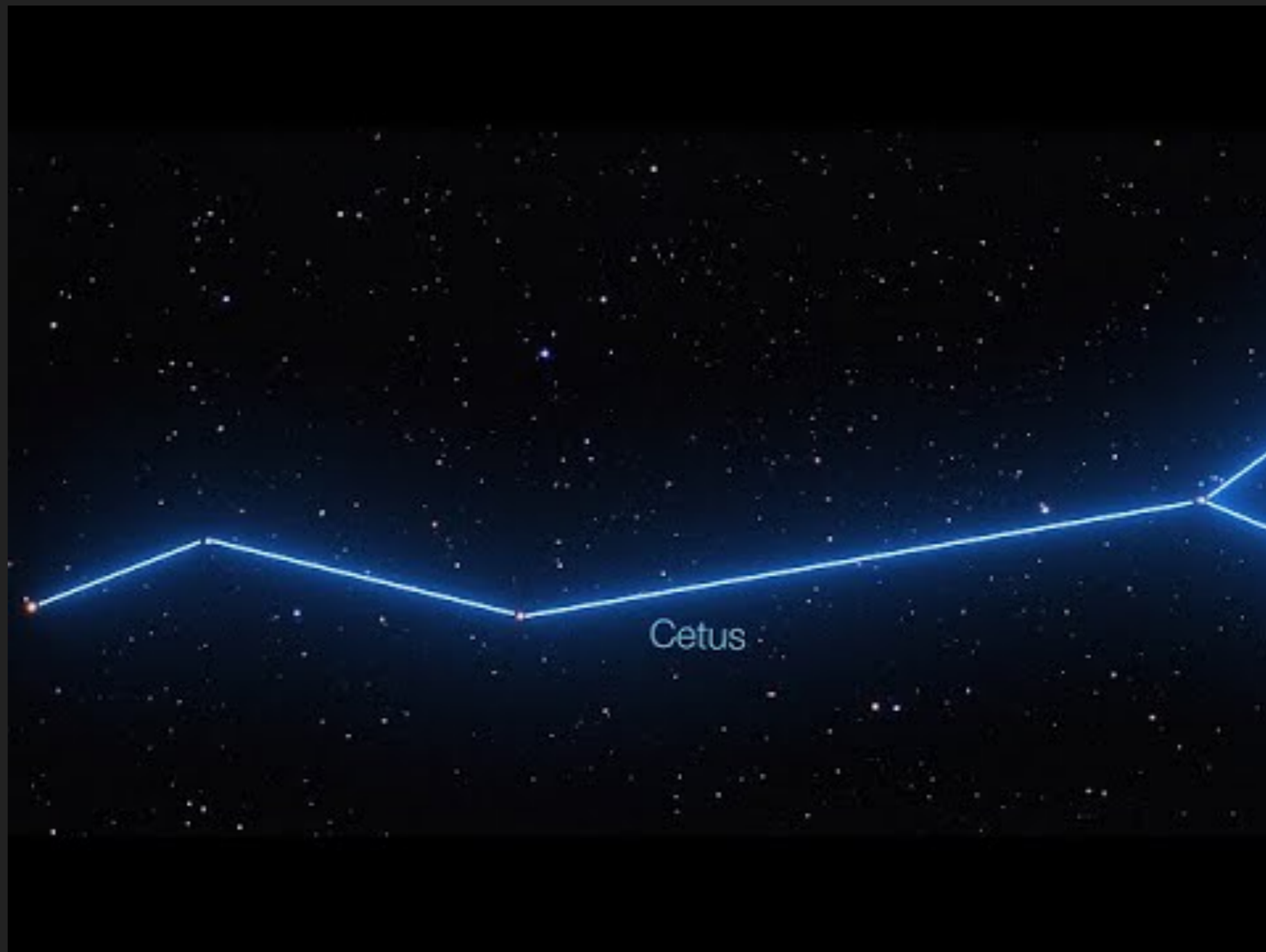
Elisa Resconi

Experimental Physics with Cosmic Particles



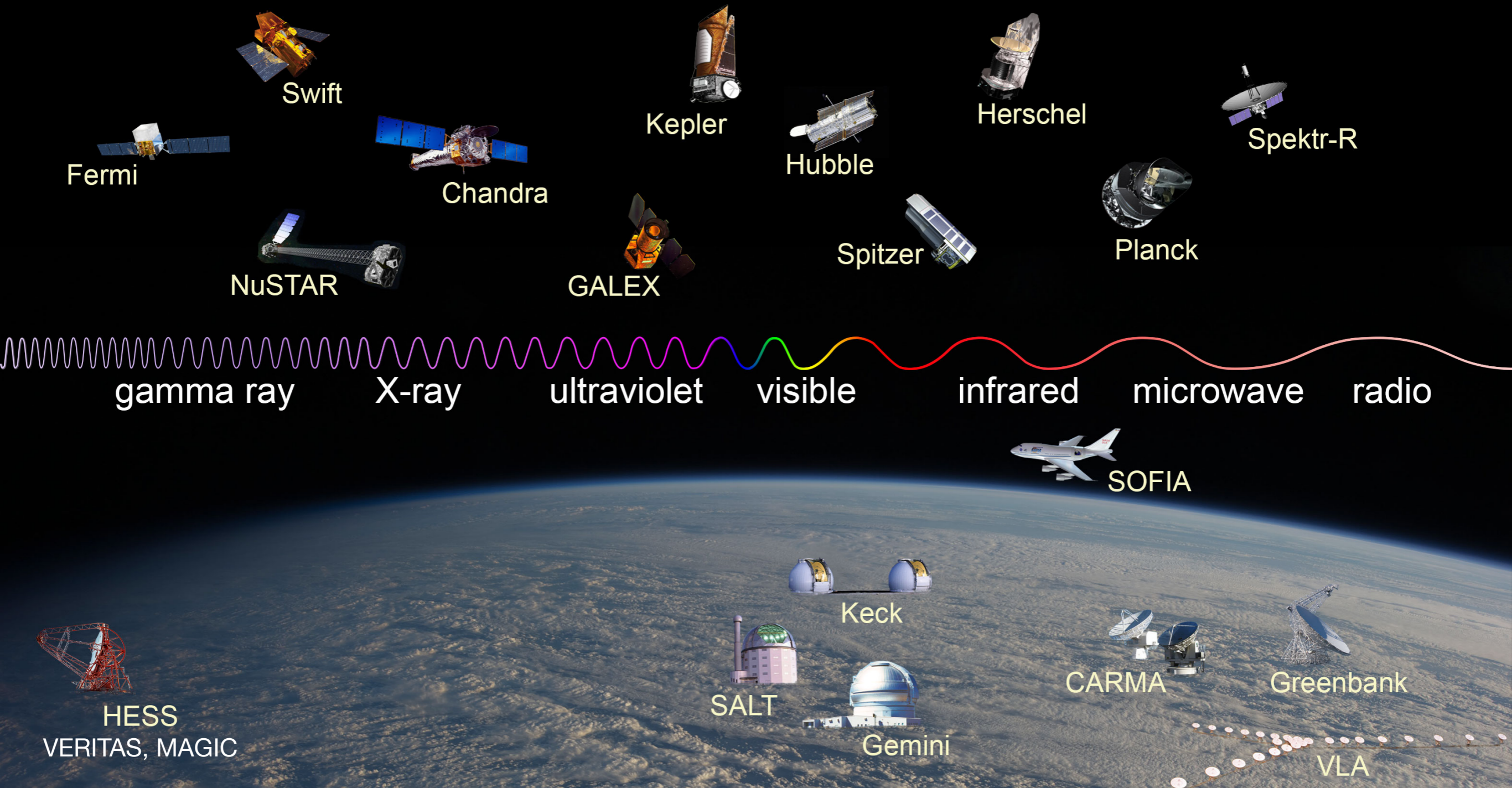
THE KNOWN UNIVERSE: THE VIEW IN PHOTONS

ESO/Digitized Sky Survey 2



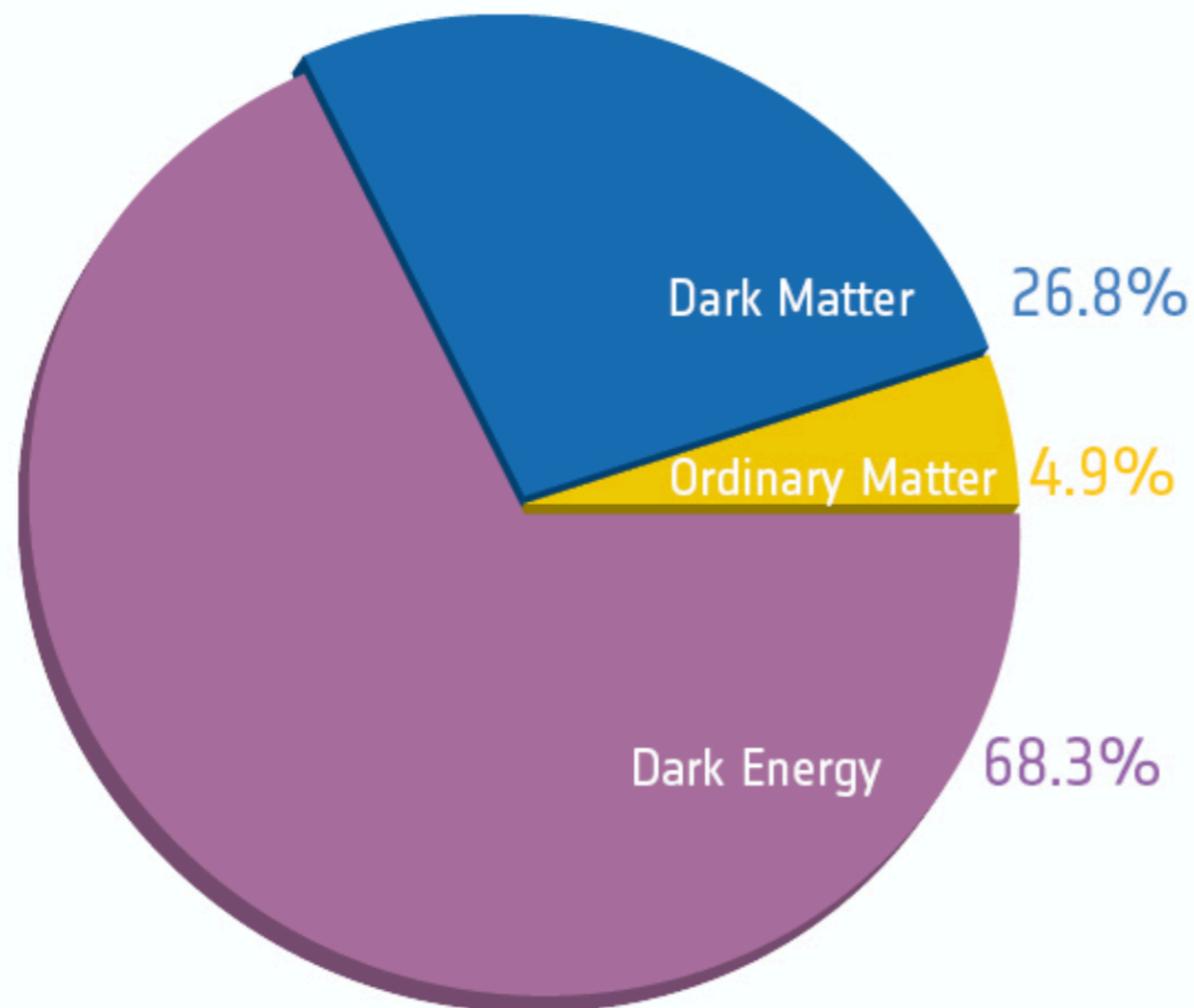
NGC1068 (M77): Visual and near UV FOcal Reducer and low dispersion Spectrograph for the Very Large Telescope (VLT)

THE KNOWN UNIVERSE: THE VIEW IN PHOTONS



THE KNOWN UNIVERSE – ONLY ~5% – MANY QUESTIONS OPEN

<https://sci.esa.int/web/planck/-/51557-planck-new-cosmic-recipe>



Why (active) galaxies don't fly apart? Dark Matter?

Why (active) galaxies don't collapse? SuperMassive Black Holes? Star forming regions?

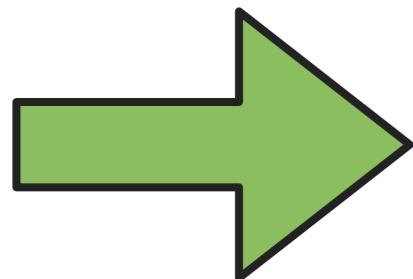
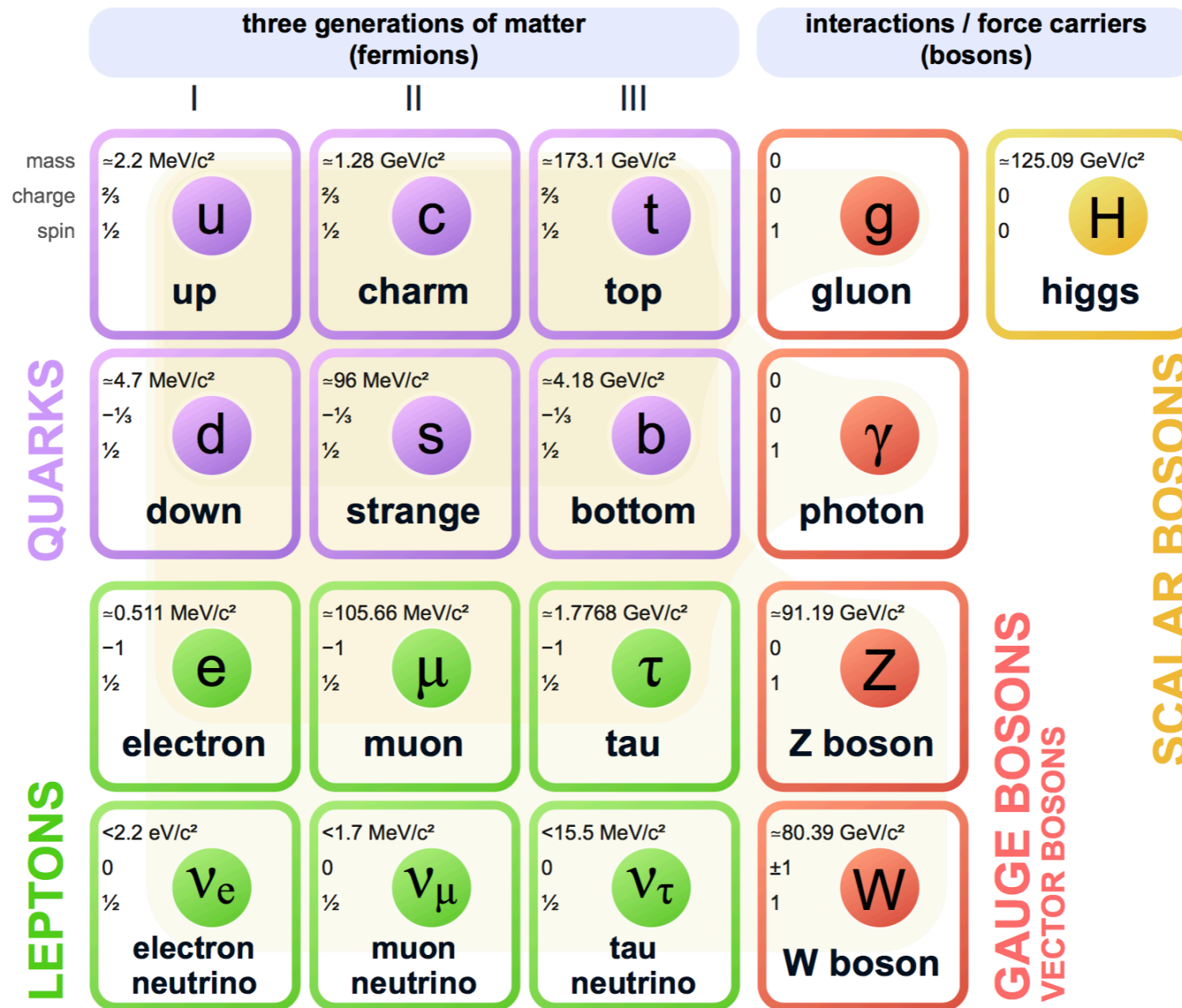
What's the role of Cosmic Rays in (active) galaxies?

What is the matter state and interactions around the event horizon?

.....

BEYOND PHOTONS: WHICH OTHER PARTICLE MESSENGER?

Standard Model of Elementary Particles



THE IDEA OF NEUTRINO ASTRONOMY AND APPROACHES

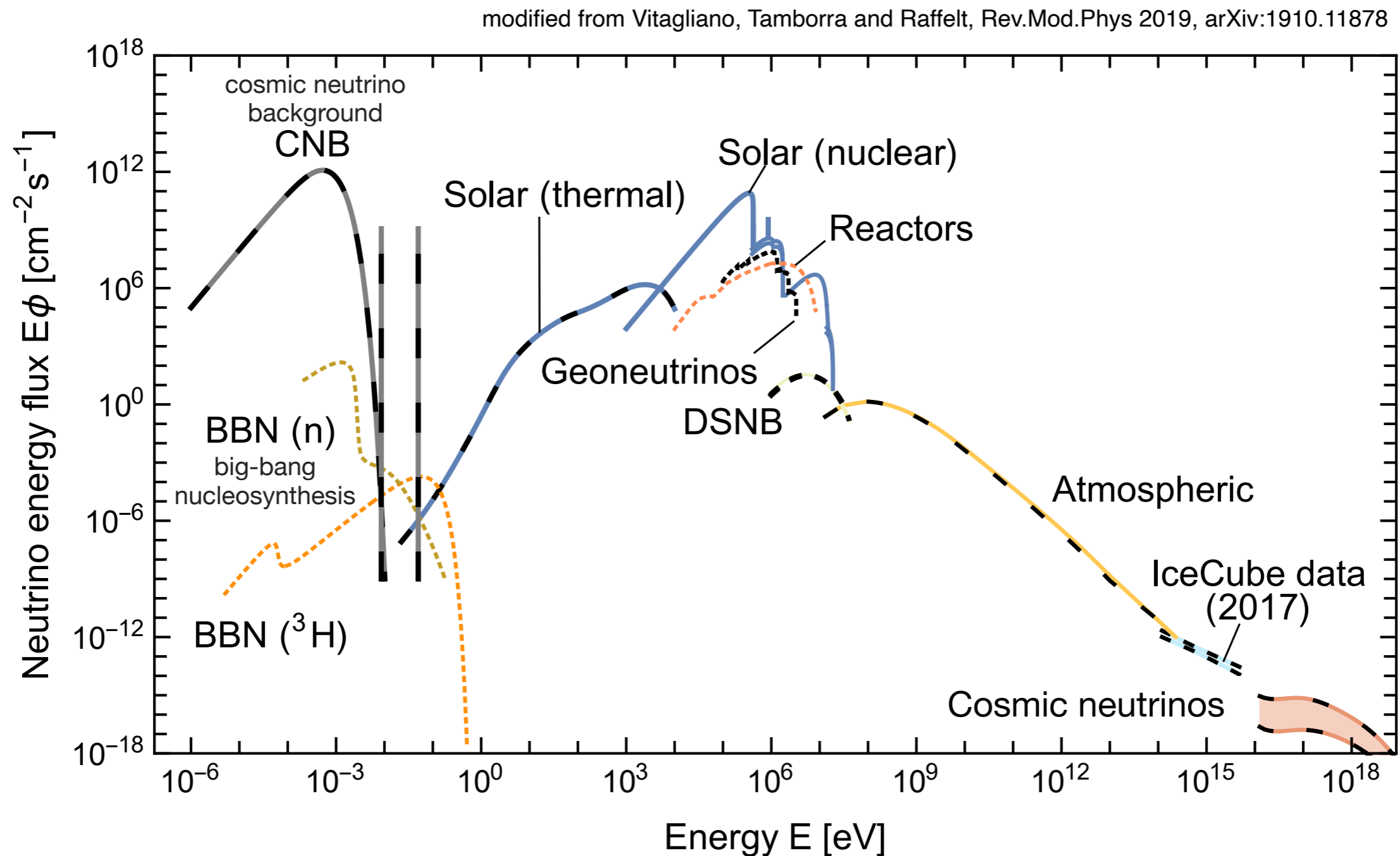
K. Greisen, "Cosmic ray showers," Ann. Rev. Nucl. Part. Sci. 10 (1960) 63–108.

F. Reines, "Neutrino interactions," Ann. Rev. Nucl. Part. Sci. 10 (1960) 1–26.

M.A. Markov, "On high energy neutrino physics," Proc. Int. Conference on High Energy Physics at Rochester (1960) 578–581.

- *interest in the possibility of detecting cosmic neutrinos „stems from the **weak interaction of neutrinos** with matter, which means that **they propagate essentially unchanged in direction and energy** from their point of origin [..] and so carry information which may be unique in character.” (F. Reines)*
- *use a large volume of water in **mine** (Greisen)*
- *use the **deep ocean** or water in a lake to study atmospheric neutrinos (Markov)*

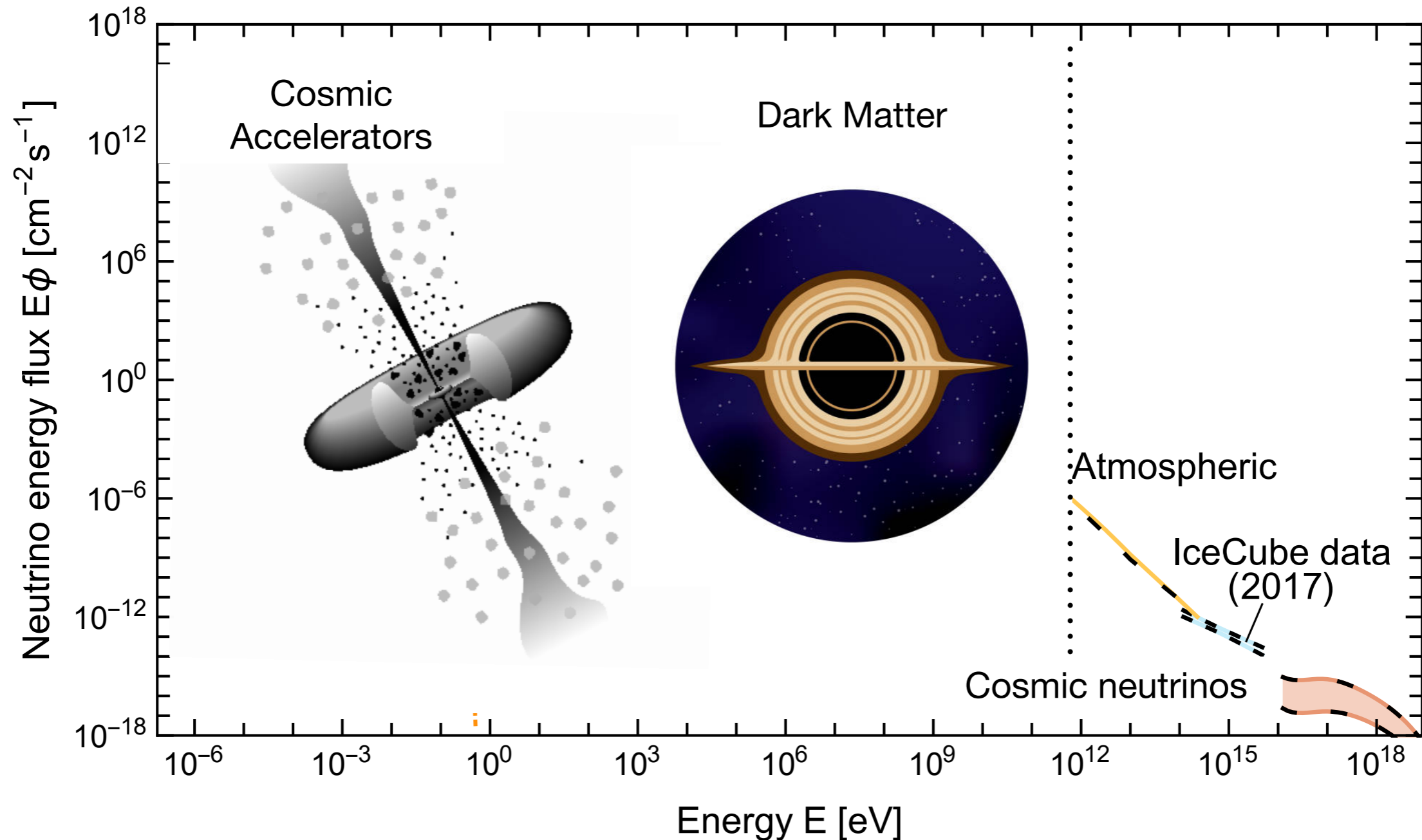
NEUTRINOS FROM THE UNIVERSE: BROAD BAND EMISSION



Grand Unified Neutrino Spectrum (GUNS) at Earth integrated over directions and flavors

WHY HIGH ENERGY NEUTRINOS?

Learn about the darkest and most energetic mechanisms in the universe



THE UNKNOWN UNIVERSE EXPLORED IN NEUTRINOS: ICECUBE



THE ICECUBE NEUTRINO OBSERVATORY

IceCube Lab

50 m



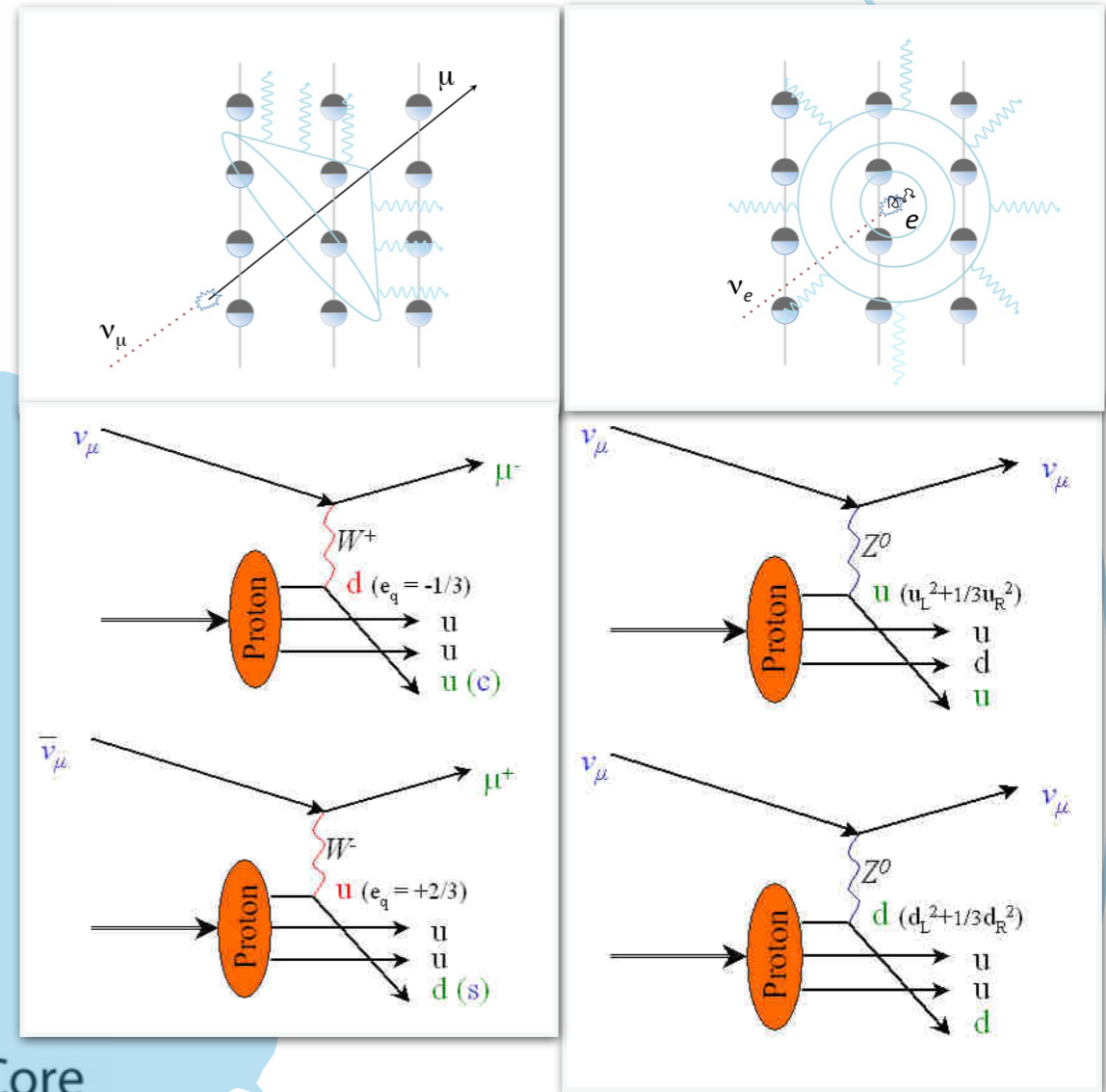
1450 m

Digital Optical Modules

2450 m

2820 m

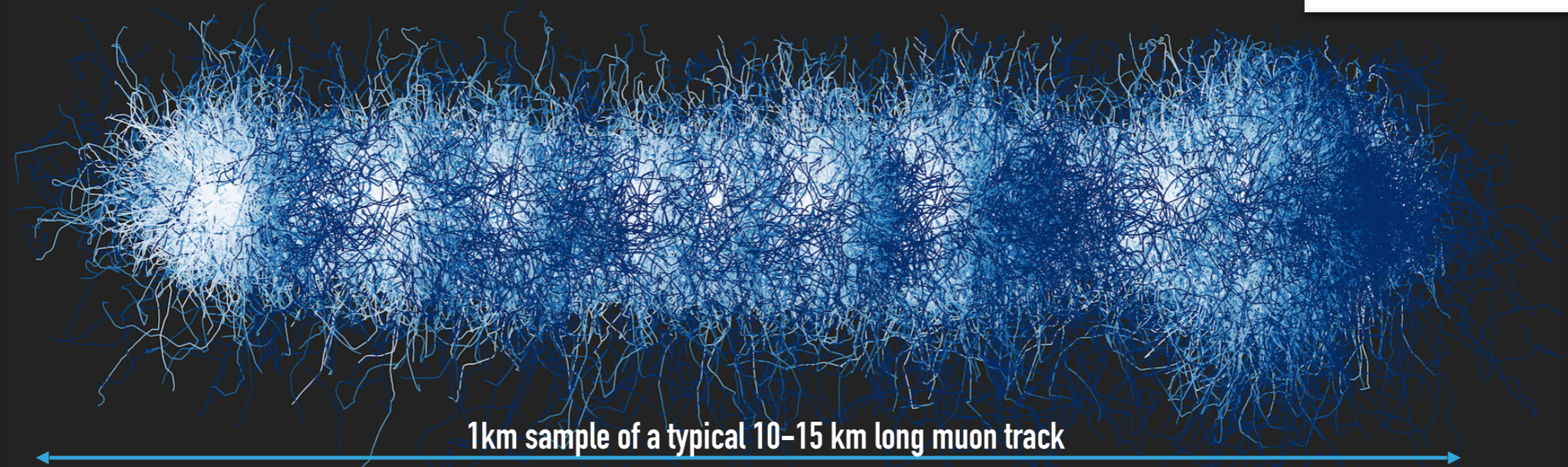
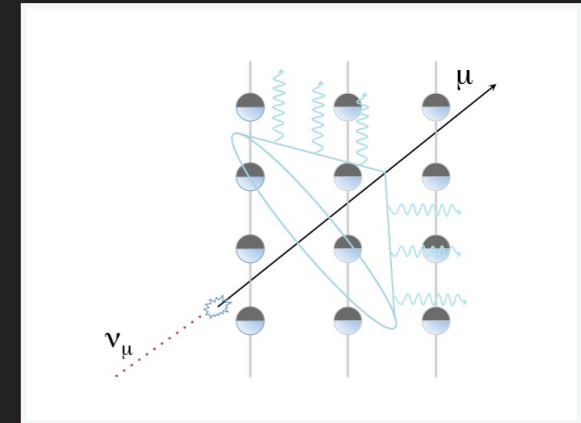
Deep Core



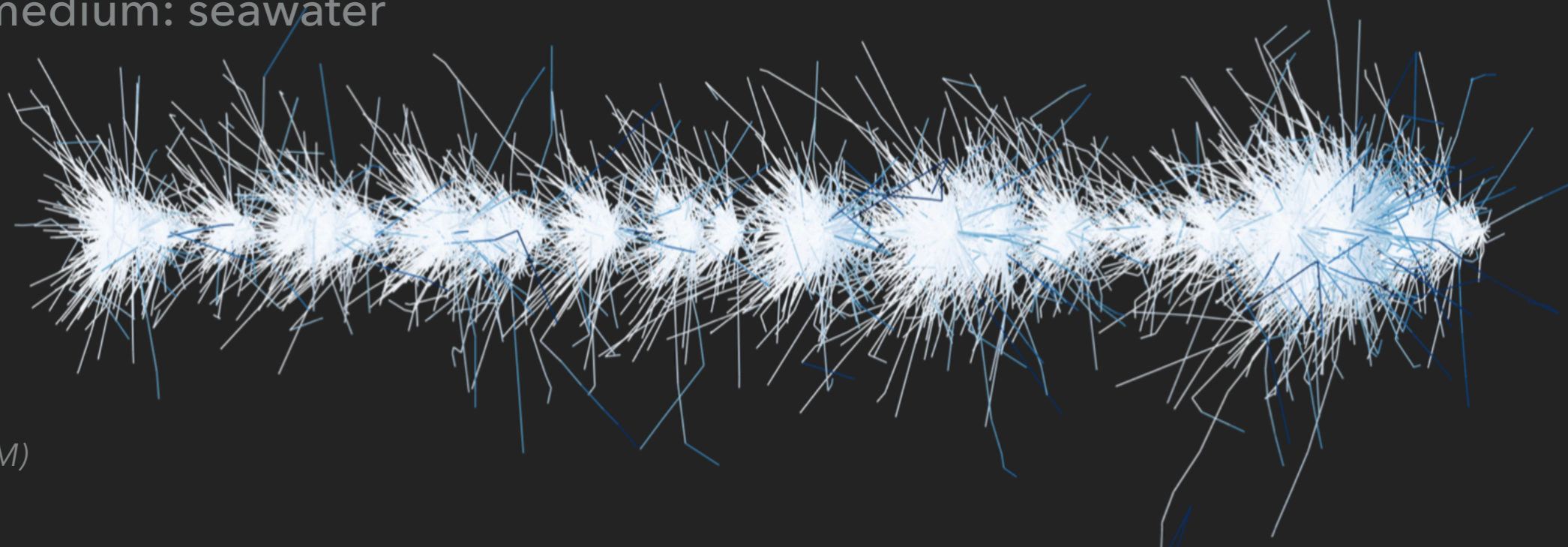
HORIZONTAL HIGH ENERGY MUONS: THE SIGNATURE

1 PeV horizontal muon

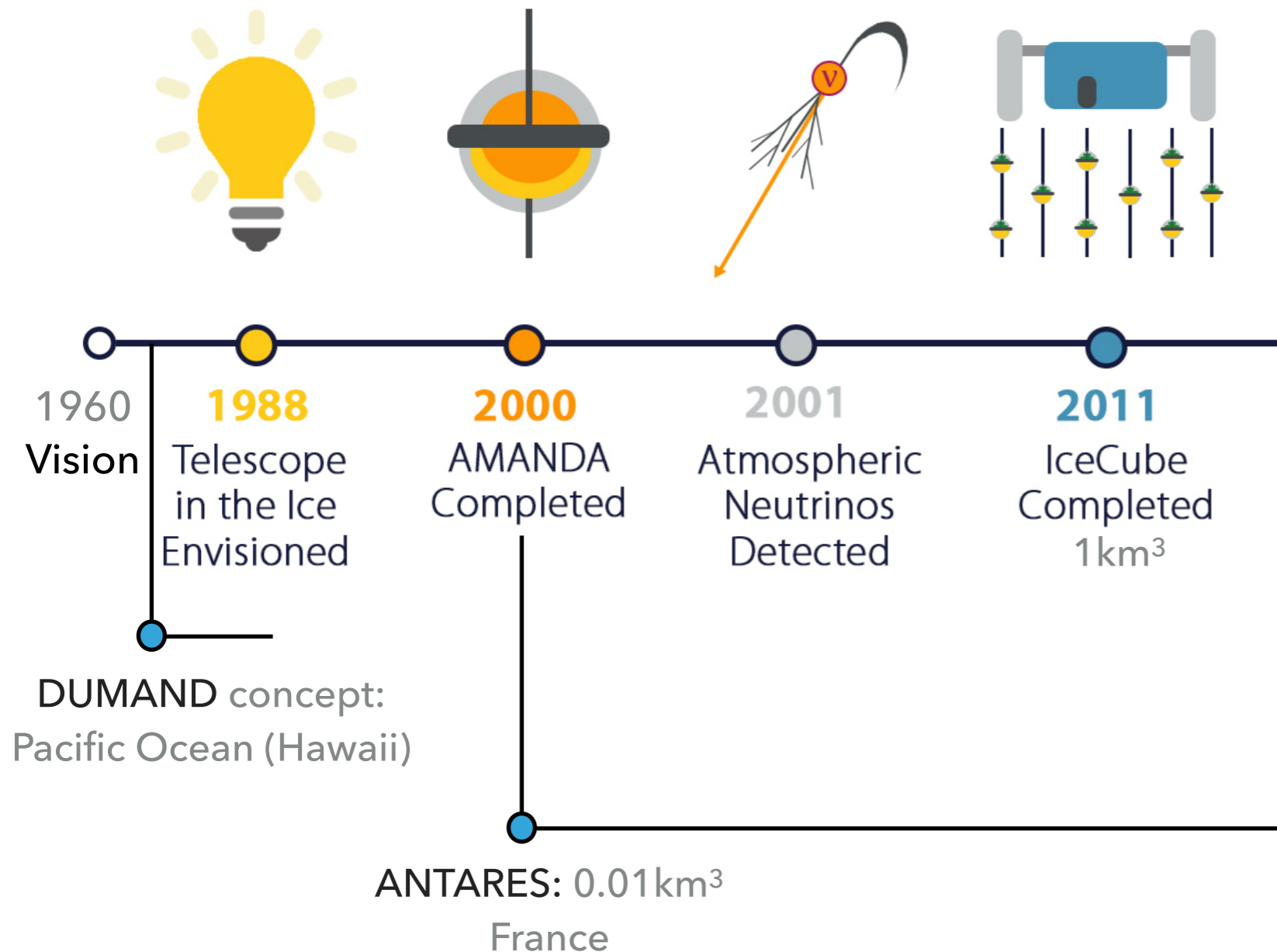
medium: IceCube ice

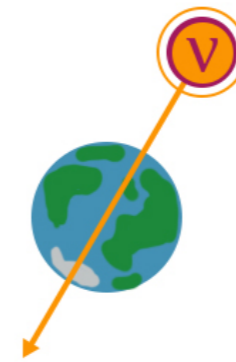
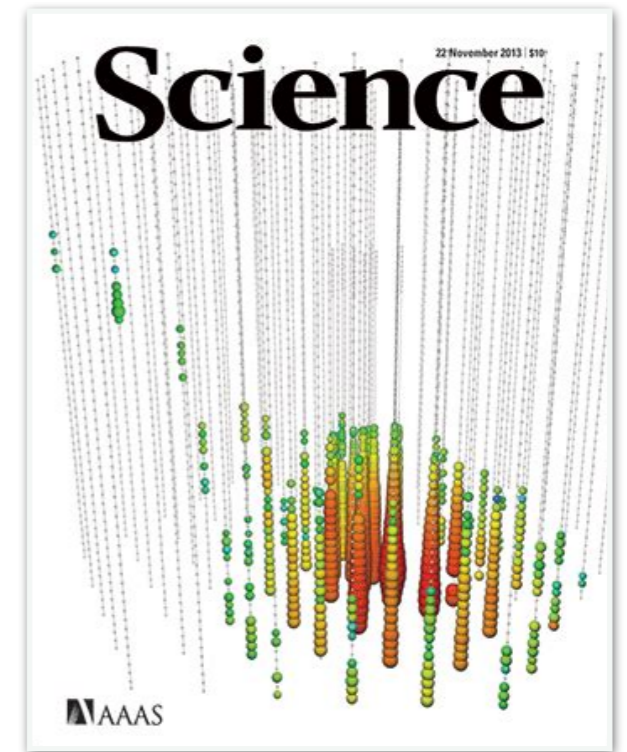
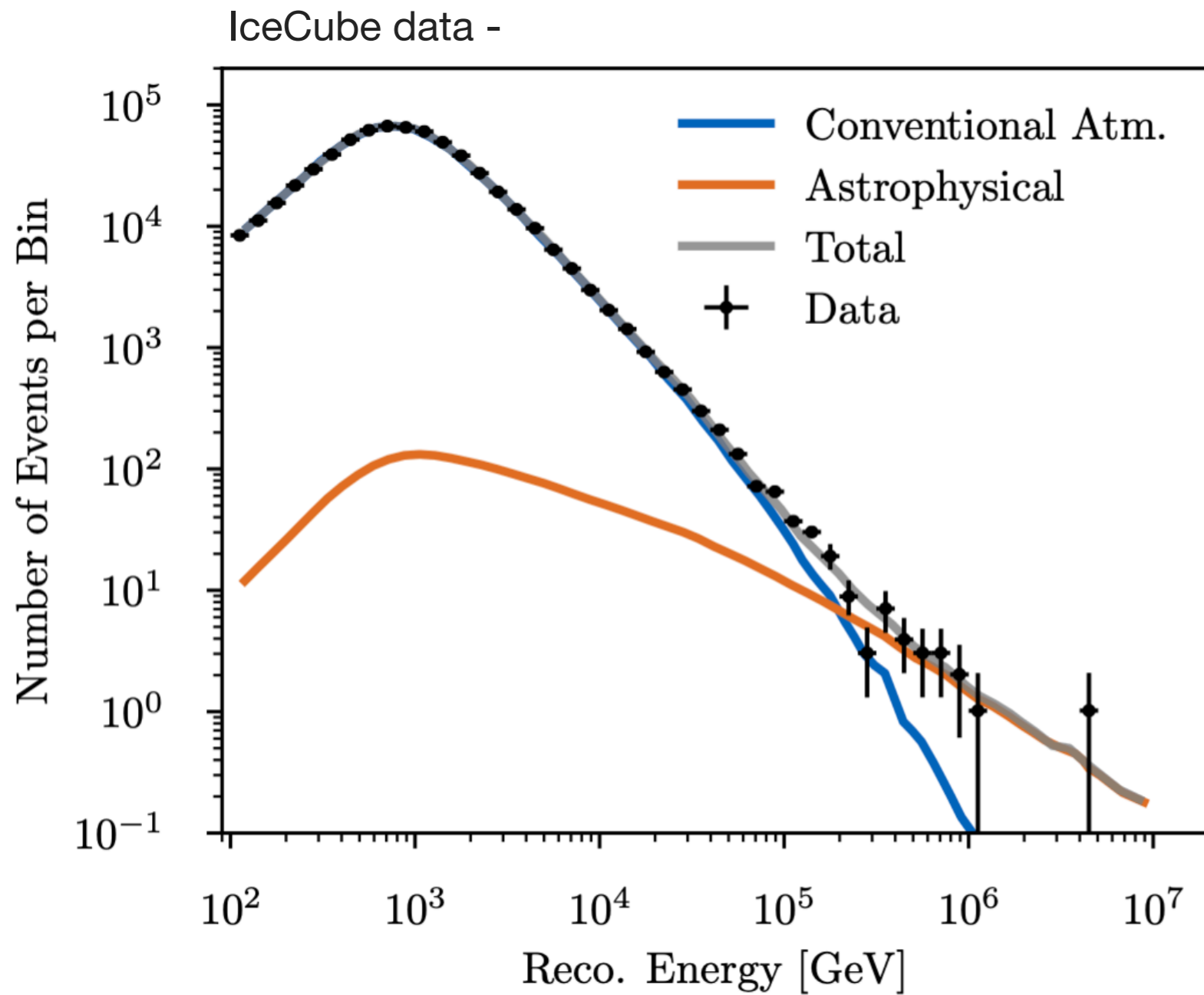


medium: seawater



Milestones in Neutrino Astronomy



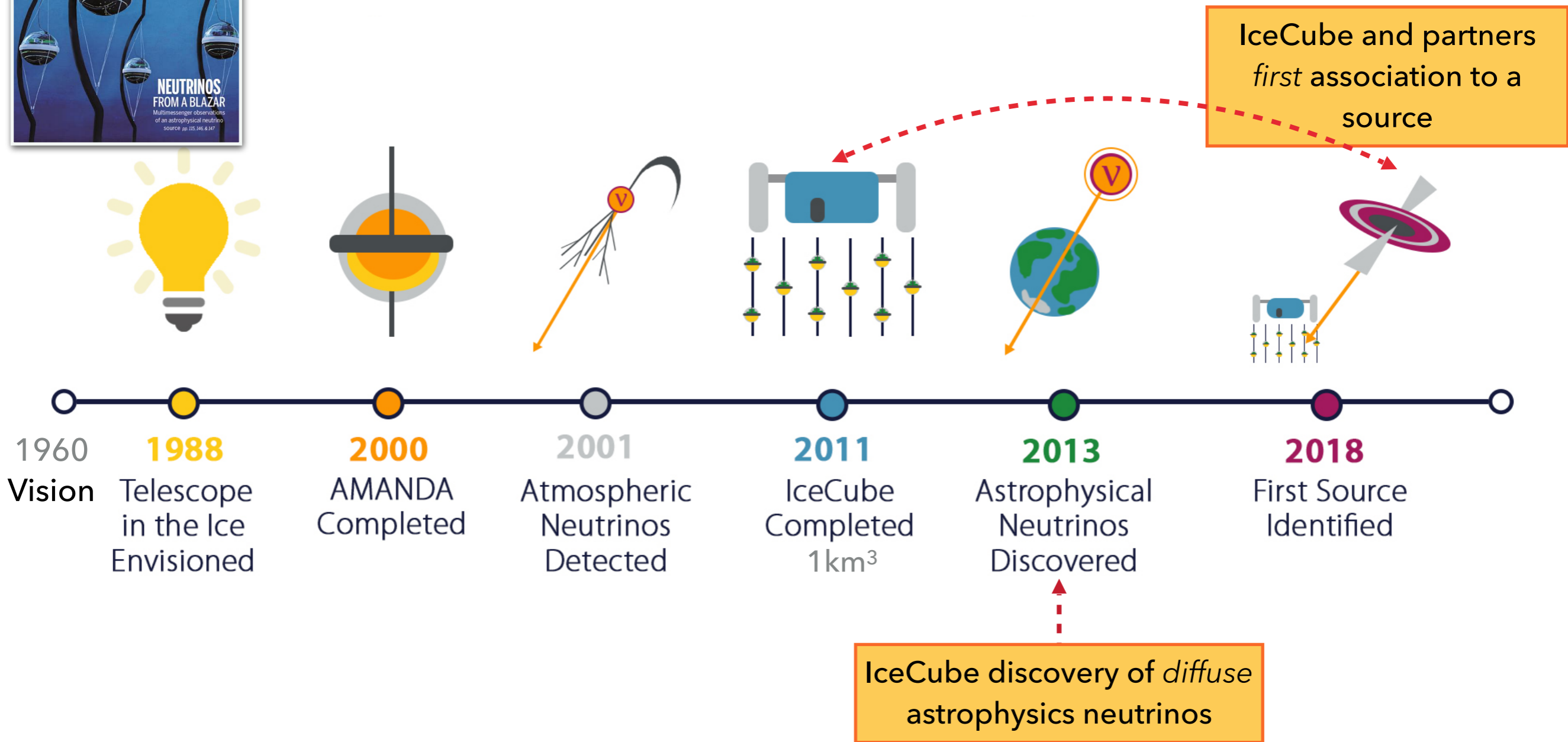


2013
Astrophysical
Neutrinos
Discovered

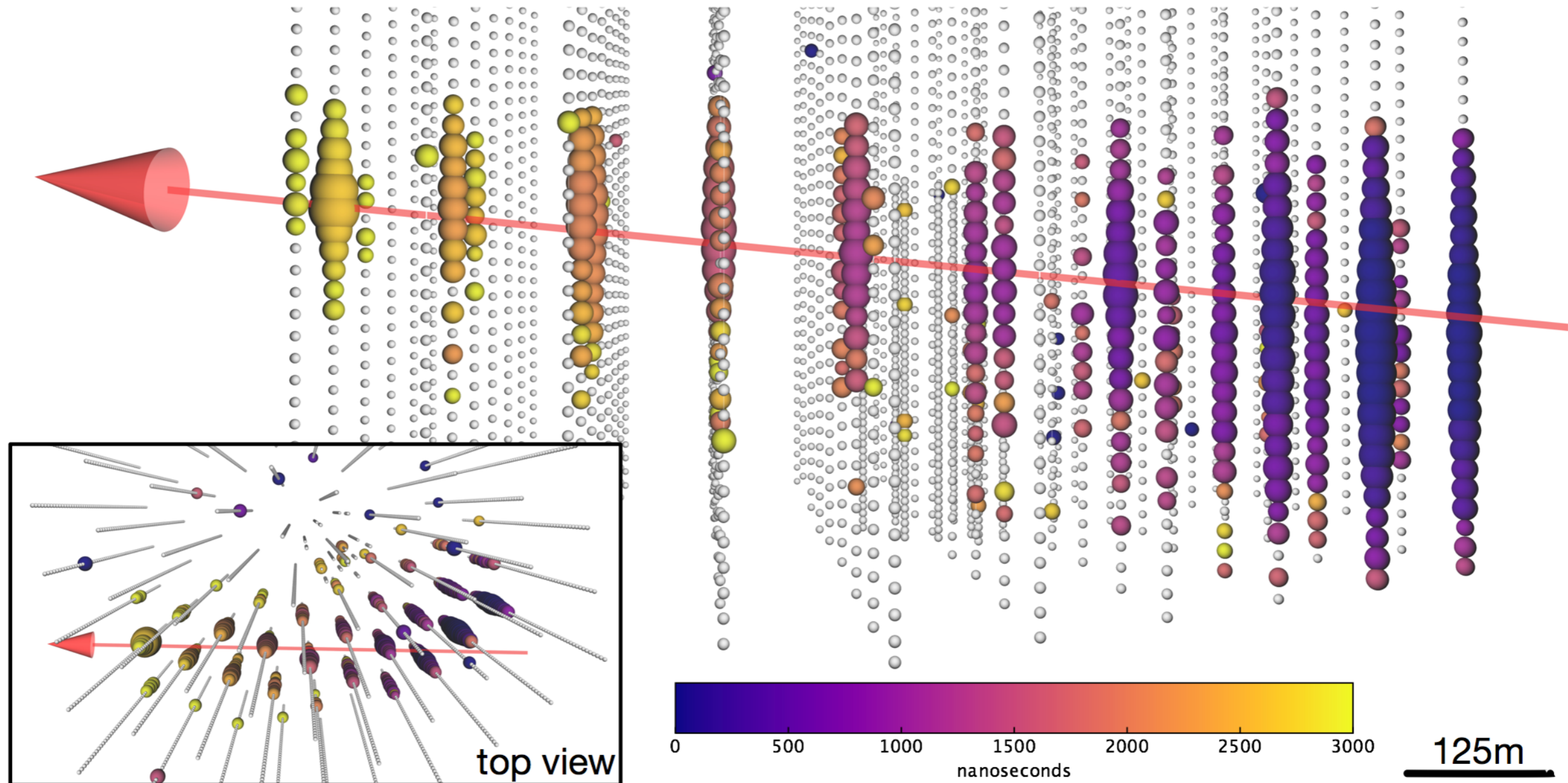
IceCube discovery of *diffuse*
astrophysics neutrinos



Milestones in Neutrino Astronomy



1) ICECUBE-170922A: NEUTRINO ALERT [~ 290 TEV, DEC ~ 5.72 DEG]



"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A", The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. **Science 361, 2018**

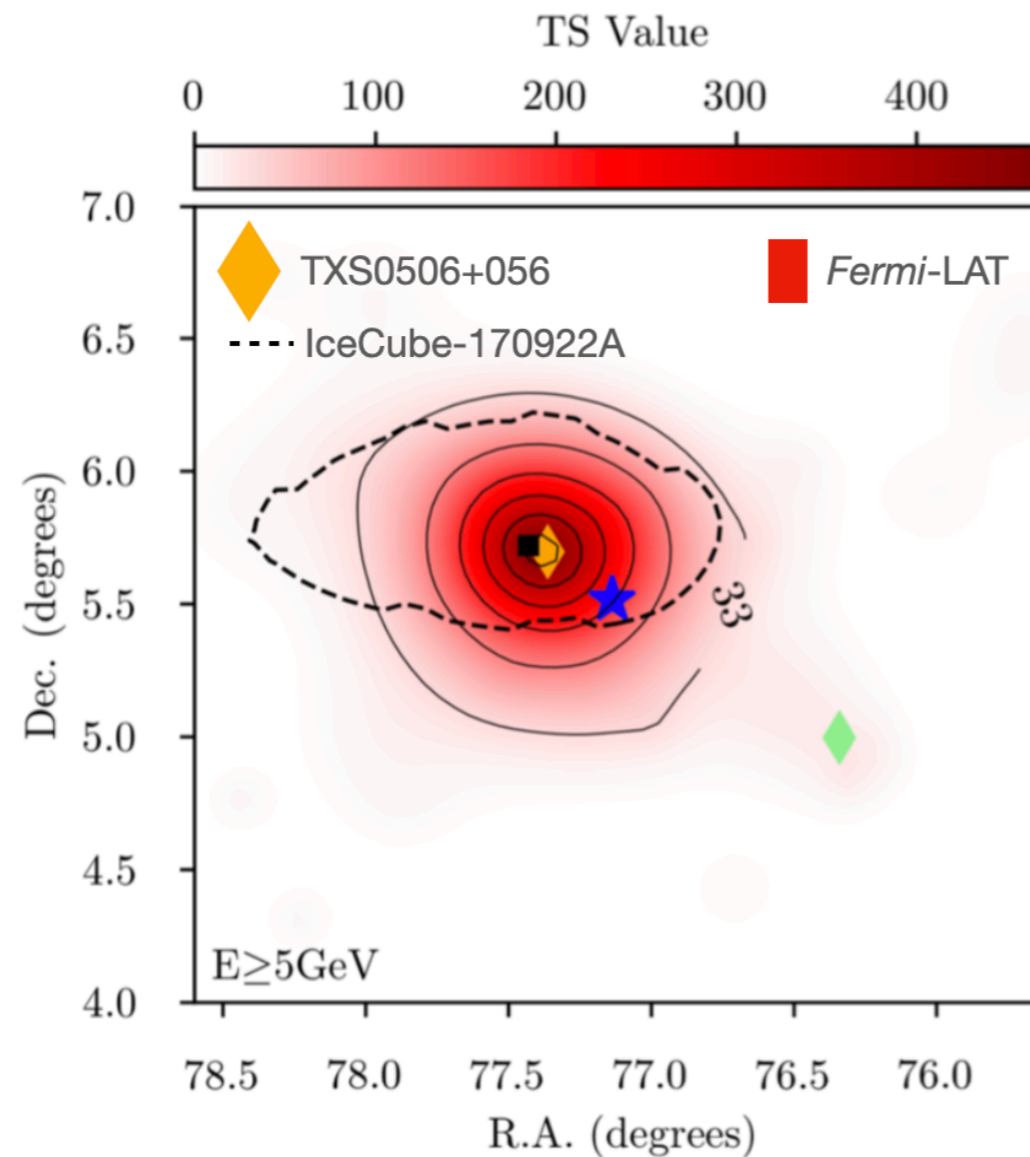
2) More than twenty instruments reacted to the neutrino alert

Follow-up detections of IC170922 based on public telegrams

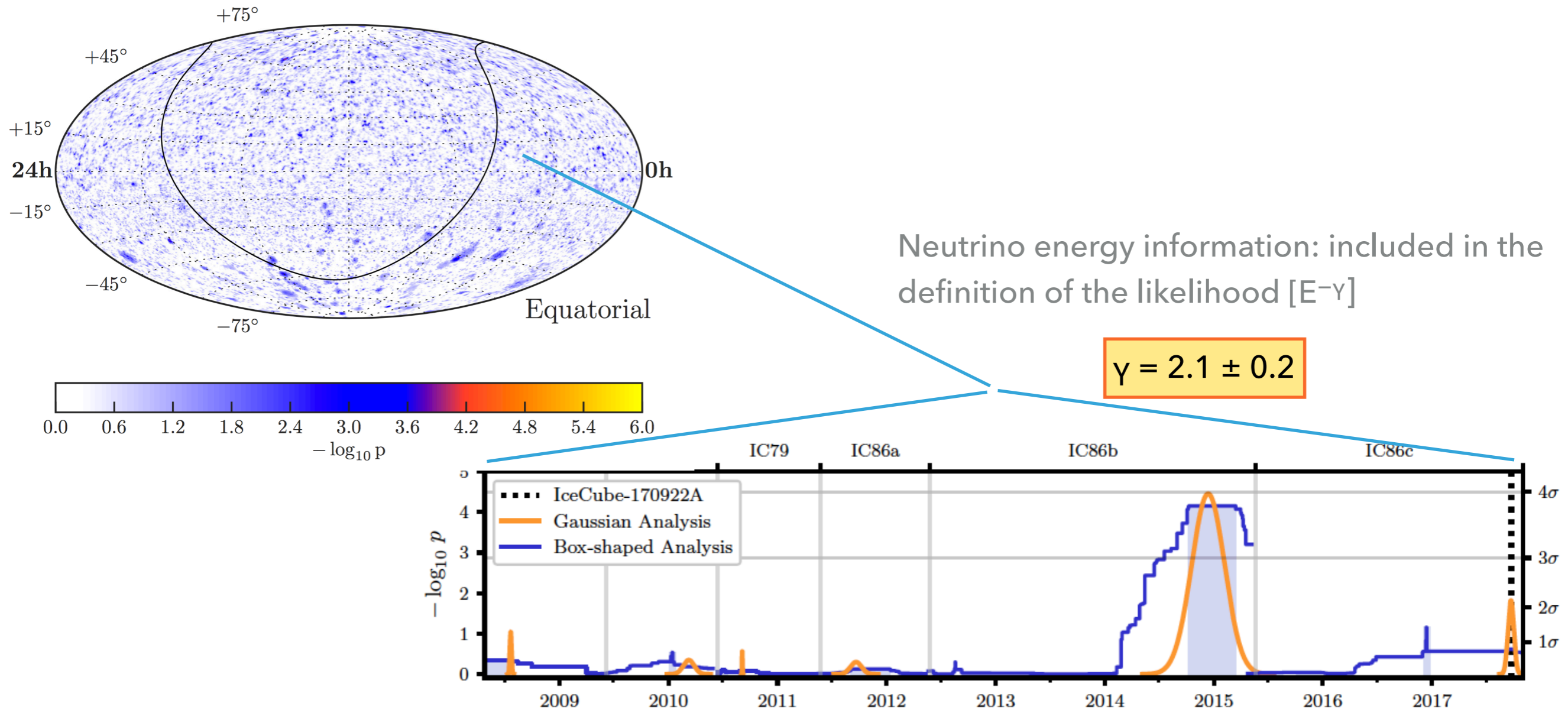


3) Identification of a flaring blazar: TXS 0506+056

“Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A”, The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, 2018



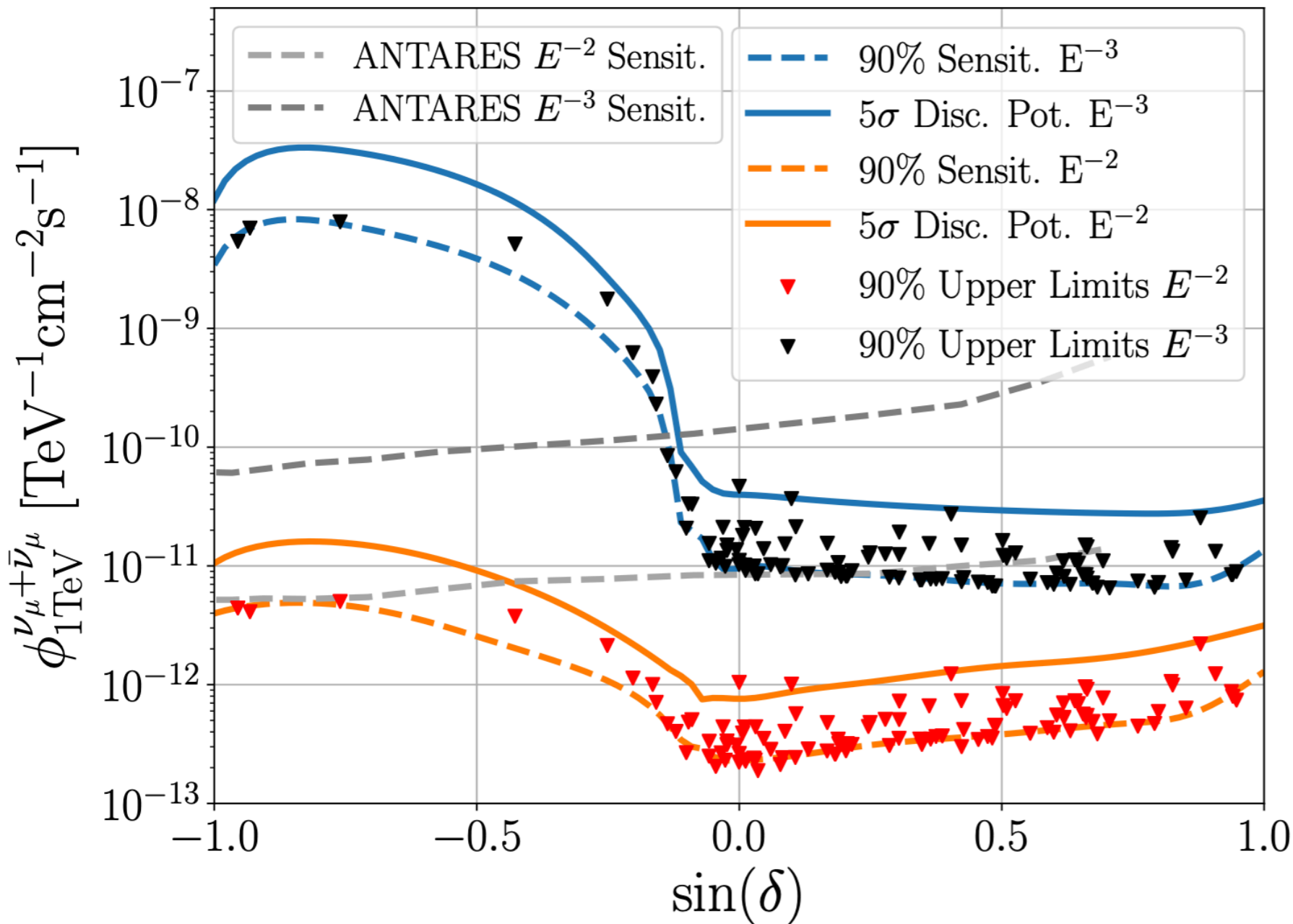
4) Identification of more neutrinos from the TXS 0506+056



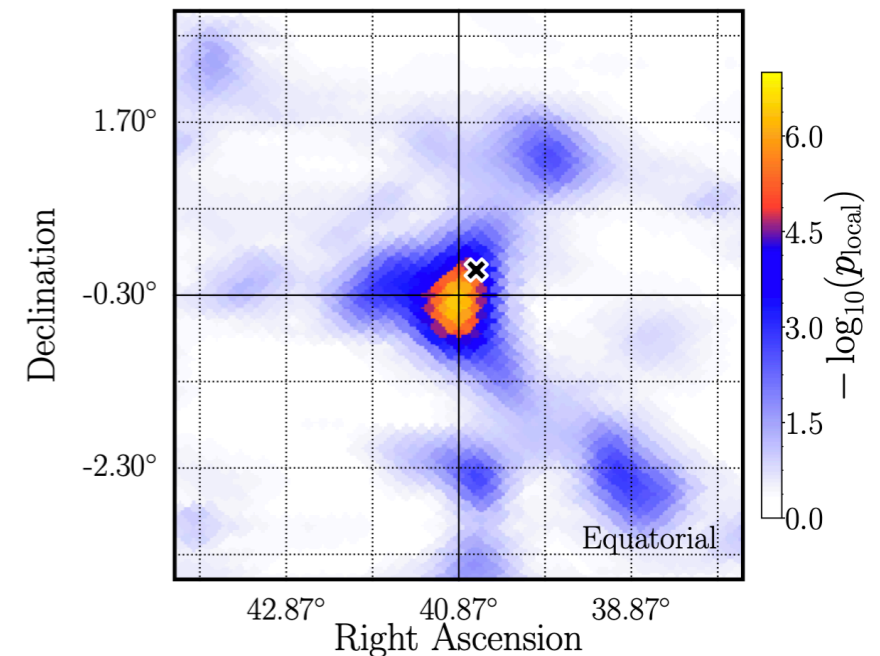
"Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert", IceCube Collaboration: M.G. Aartsen et al. **Science** 361, 147-151 (2018).

WHAT ELSE IN THE NEUTRINO SKY?

"Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data". *Phys. Rev. Lett.* **124**, 051103

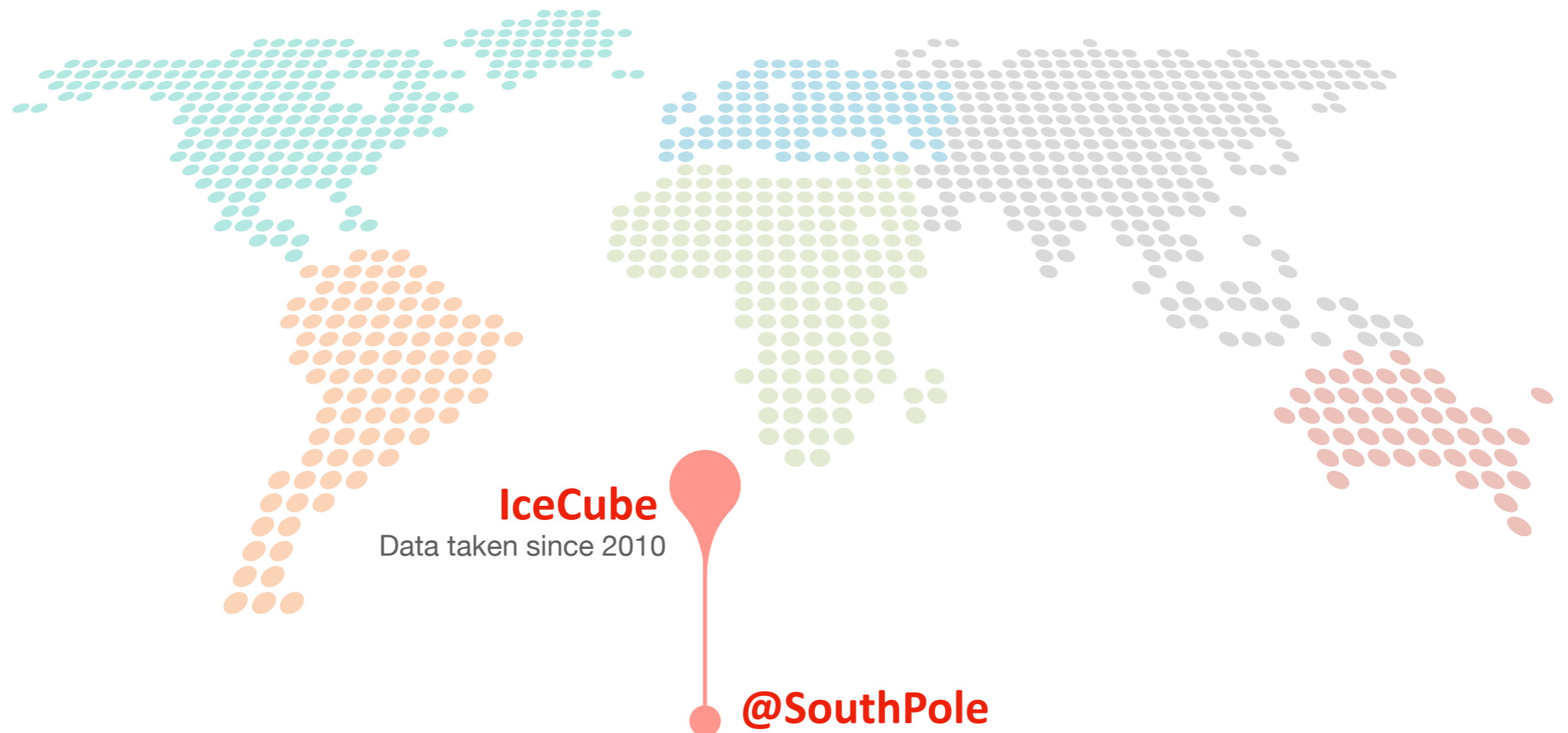


2.9 σ (post-trial) from NGC 1068

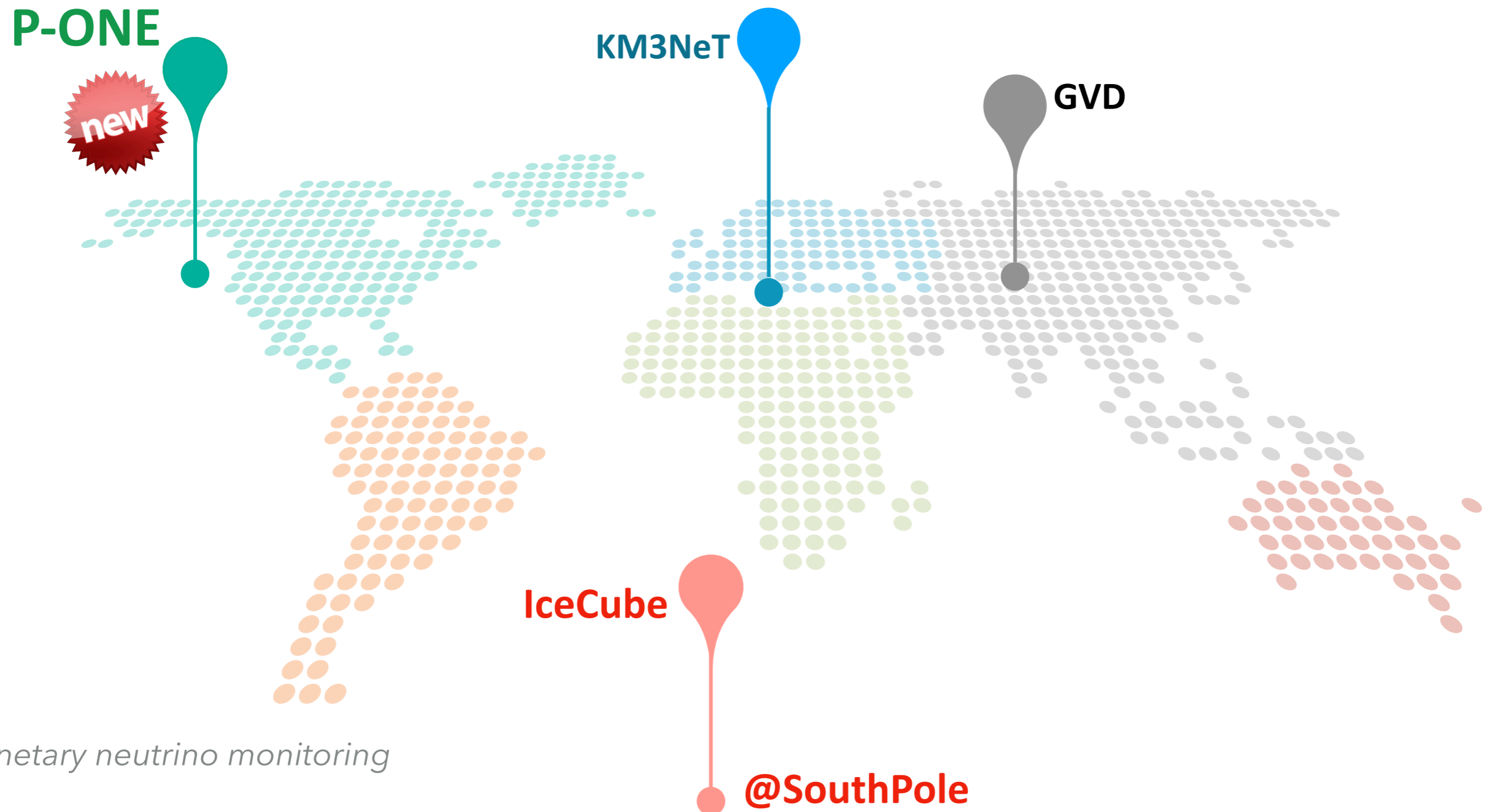


After 10 years of exposure from IceCube:
the dawn of neutrino astronomy

NEUTRINO TELESCOPE(S) SENSITIVE TO TEV-PEV COSMIC NEUTRINOS



To open the neutrino sky: more neutrino telescopes & operate them together in PLEnuM*

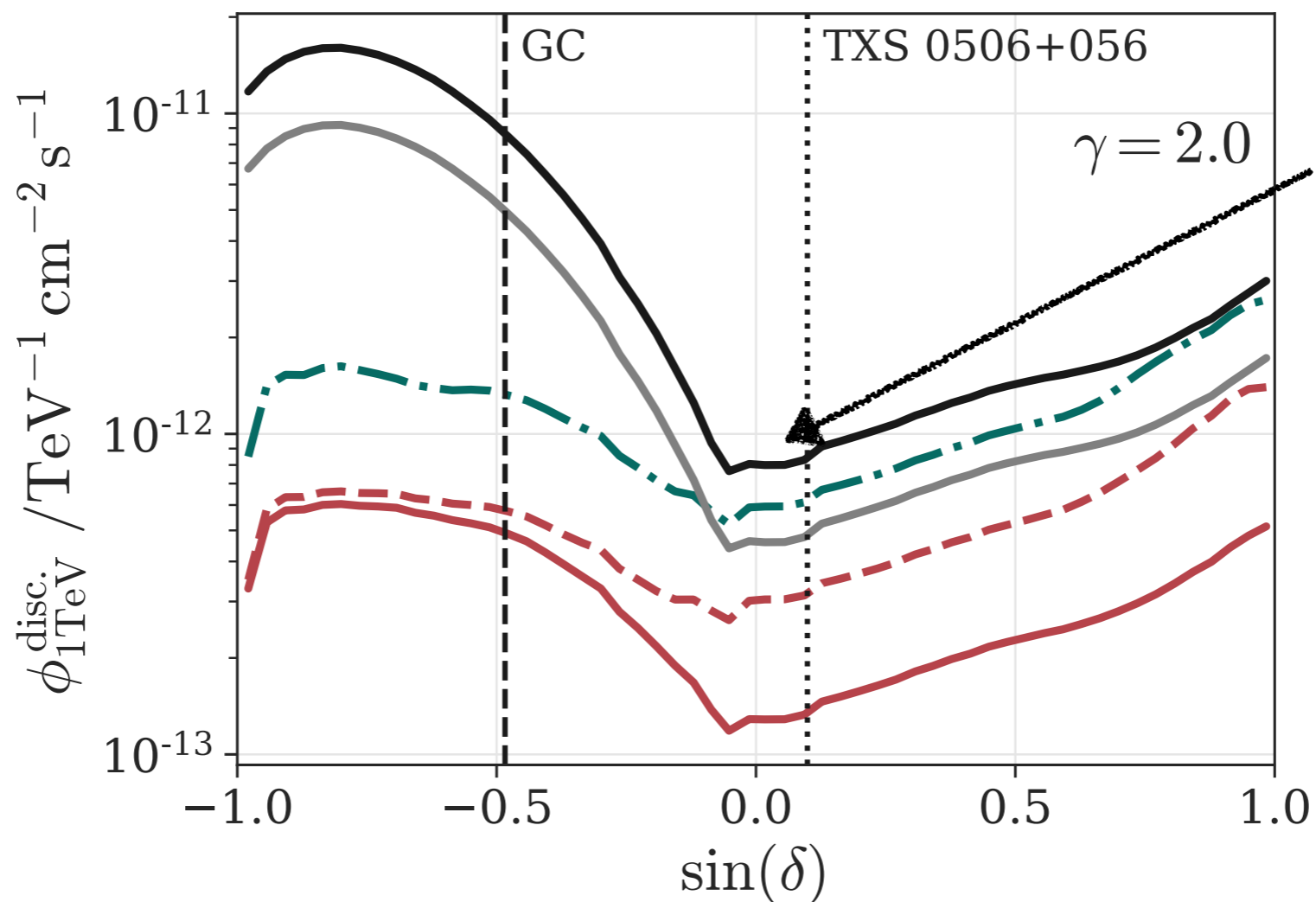


*Planetary neutrino monitoring

PLE ν M

L. Schumacher et al., PoS(ICRC2021)1185

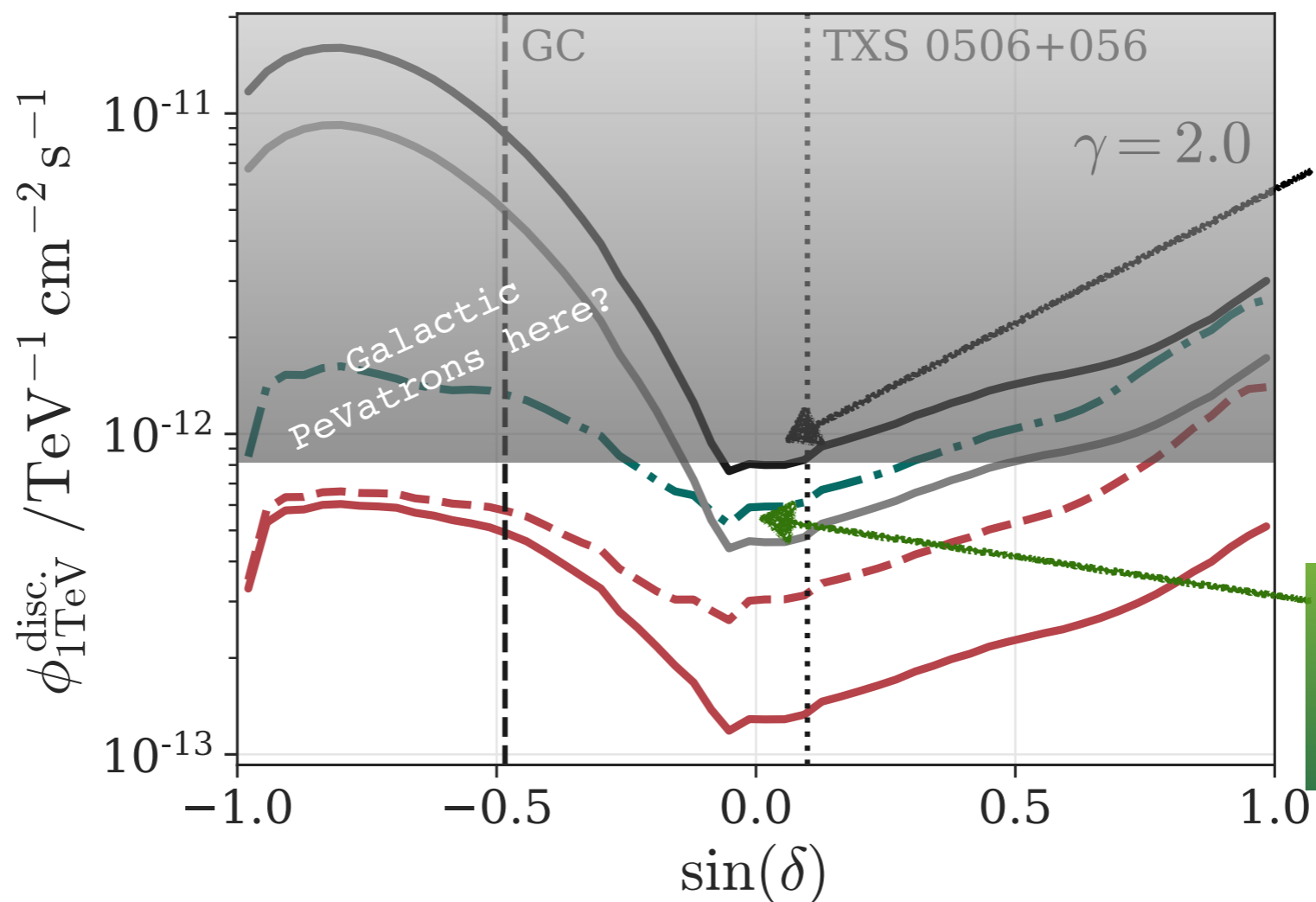
- IceCube (10yr)
- IceCube + P-ONE (10yr)
- IceCube (20yr)
- - - IceCube + PLE ν M-1 (10yr)
- IceCube + PLE ν M-2 (10yr)

FIRST HINTS
OF SOURCES
FROM ICECUBE

PLE ν M

L. Schumacher et al., PoS(ICRC2021)1185

- IceCube (10yr)
- · - IceCube + P-ONE (10yr)
- IceCube (20yr)
- - - IceCube + PLE ν M-1 (10yr)
- IceCube + PLE ν M-2 (10yr)



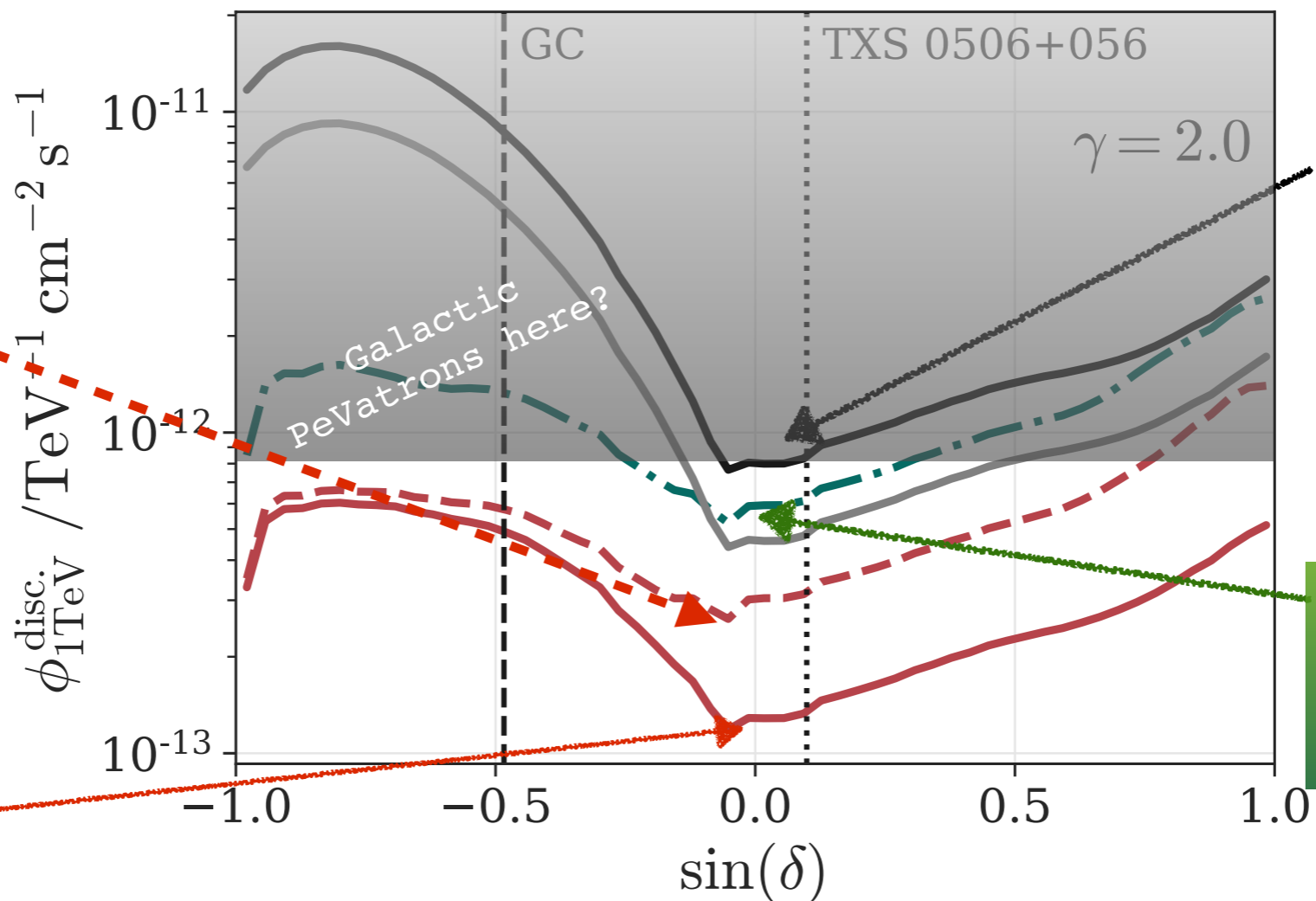
FIRST HINTS
OF SOURCES
FROM ICECUBE

+ONE NEUTRINO
TELESCOPE IN
THE NORTH

PLE ν M

L. Schumacher et al., PoS(ICRC2021)1185

- IceCube (10yr)
- · - IceCube + P-ONE (10yr)
- IceCube (20yr)
- - - IceCube + PLE ν M-1 (10yr)
- IceCube + PLE ν M-2 (10yr)



+ 3 NEUTRINO TELESCOPES IN THE NORTH

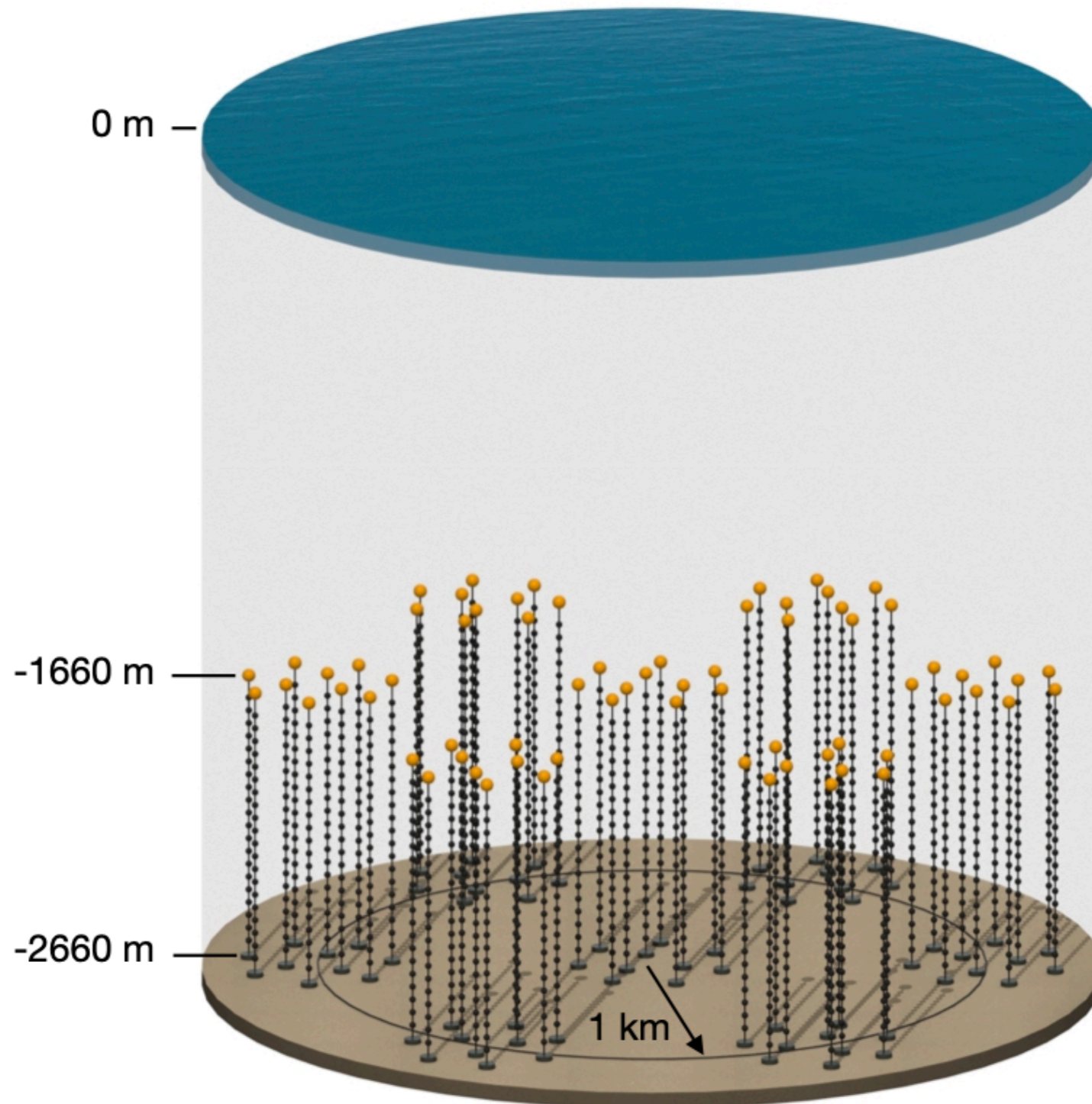
+ 3 NEUTRINO TELESCOPES IN THE NORTH + GEN2

FIRST HINTS OF SOURCES FROM ICECUBE

+ ONE NEUTRINO TELESCOPE IN THE NORTH

PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE)

P-ONE Collaboration, *Nature Astron.* 4 (2020) 10, 913–915



- 3D array of instrumented vertical line, IceCube style;
- mPMT optical sensors, KM3NeT style;
- clusters of instrumented vertical lines, GVD style.

What is new about P-ONE?

**First Neutrino Telescope
hosted by an existing
large scale oceanographic
infrastructure:
Ocean Networks Canada**



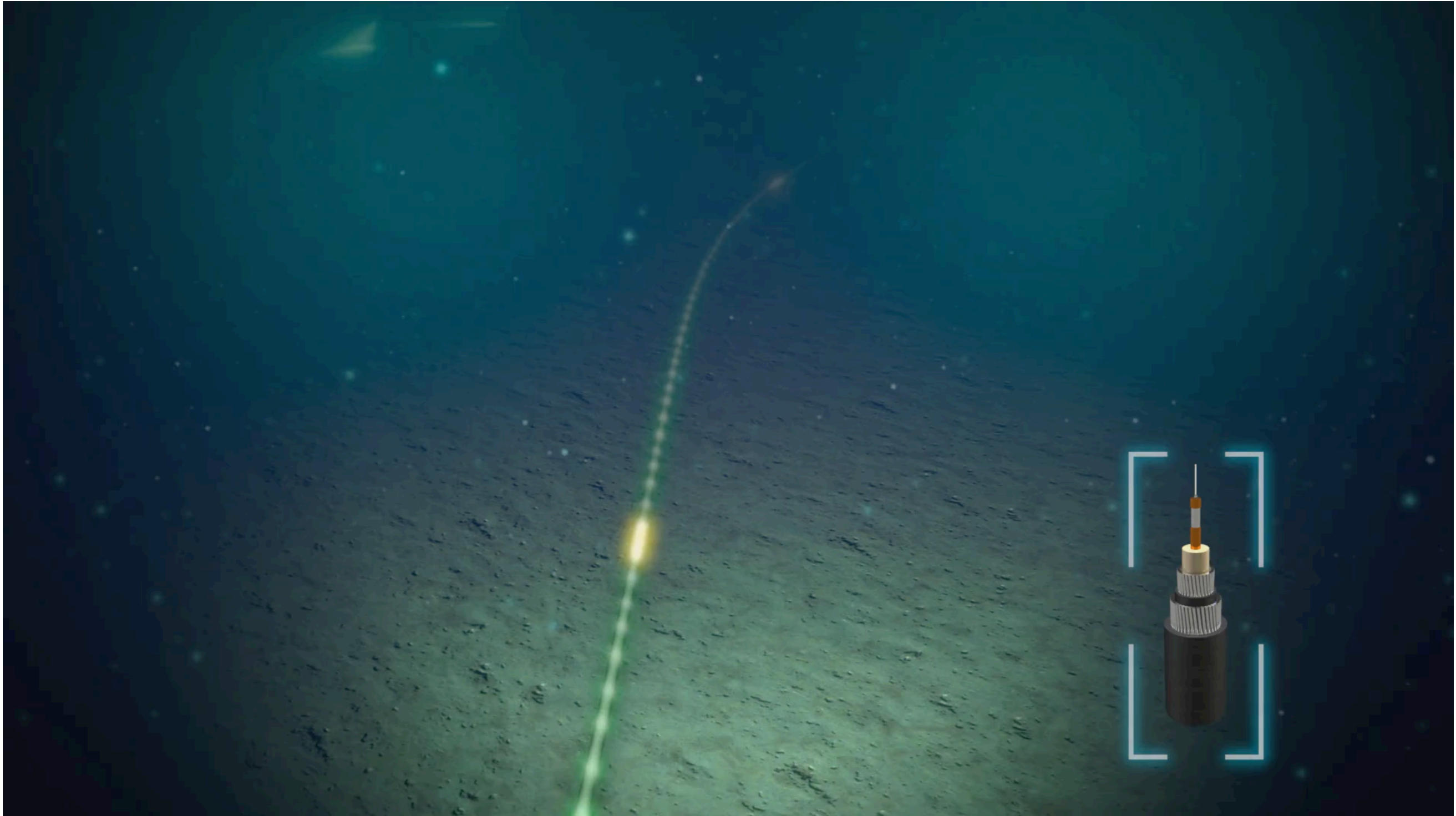
THE INTERNET-CONNECTED OCEAN OCEAN NETWORKS CANADA (UNIVERSITY OF VICTORIA)

Cabled ocean observatory: North East Pacific Time-series Underwater Networked Experiment (**NEPTUNE**), completed in 2009, multidisciplinary subsea system.

- 800 km loop of fibre-optic cables;
- Highly reliable underwater operations distributed to 5 nodes;
- Each node:
 - high-speed data link (up to 4 Gb/s per node);
 - high power (~8 kW/node);
 - read data in real time at high time resolution.

Installation of the scientific instrumentation: *plug and play*.

<https://www.oceannetworks.ca/>



THE INTERNET-CONNECTED OCEAN OCEAN NETWORKS CANADA (UNIVERSITY OF VICTORIA)

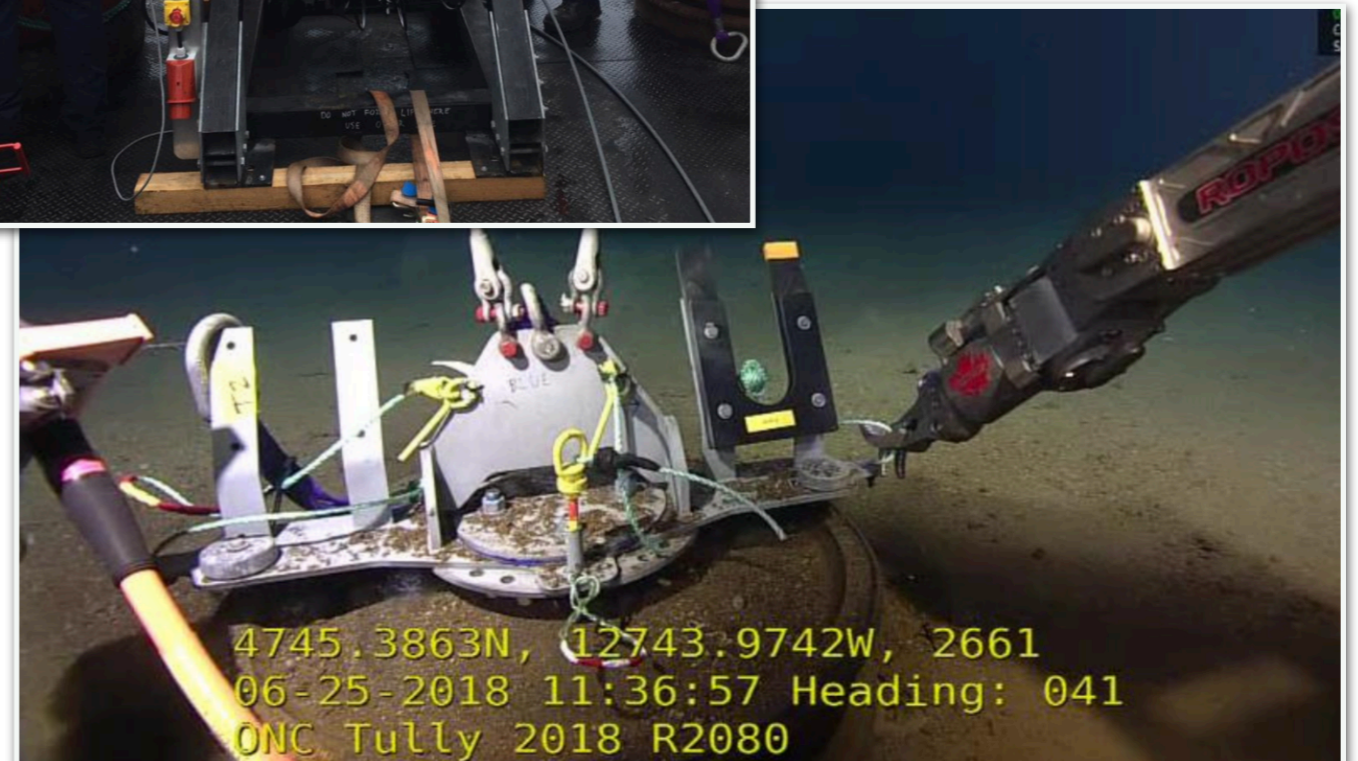
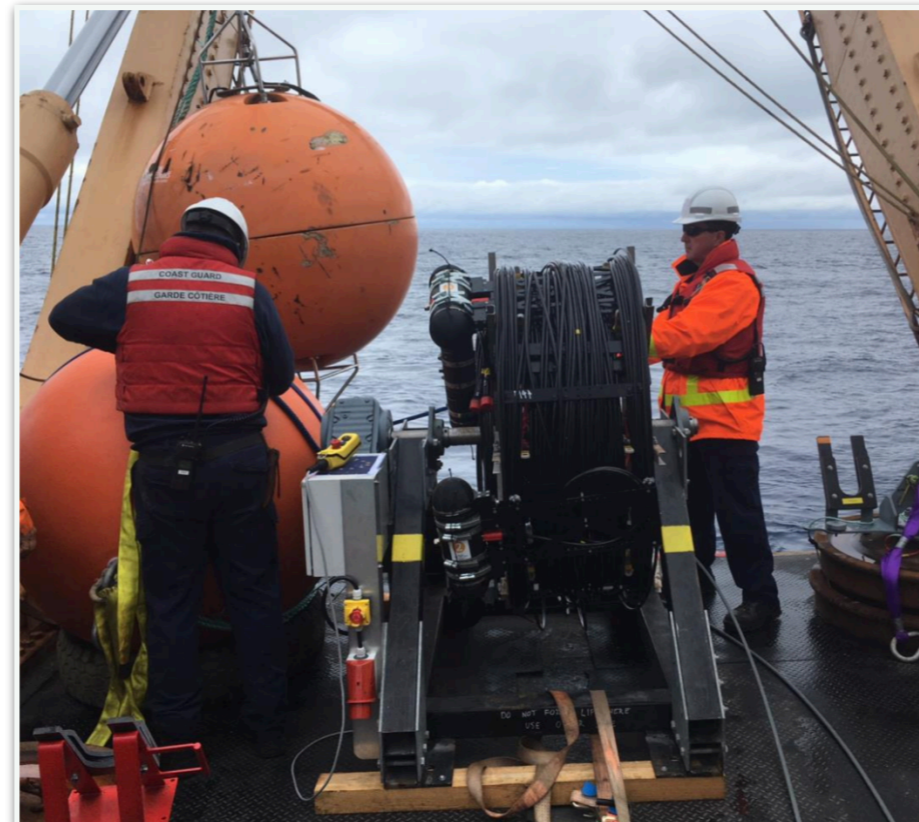
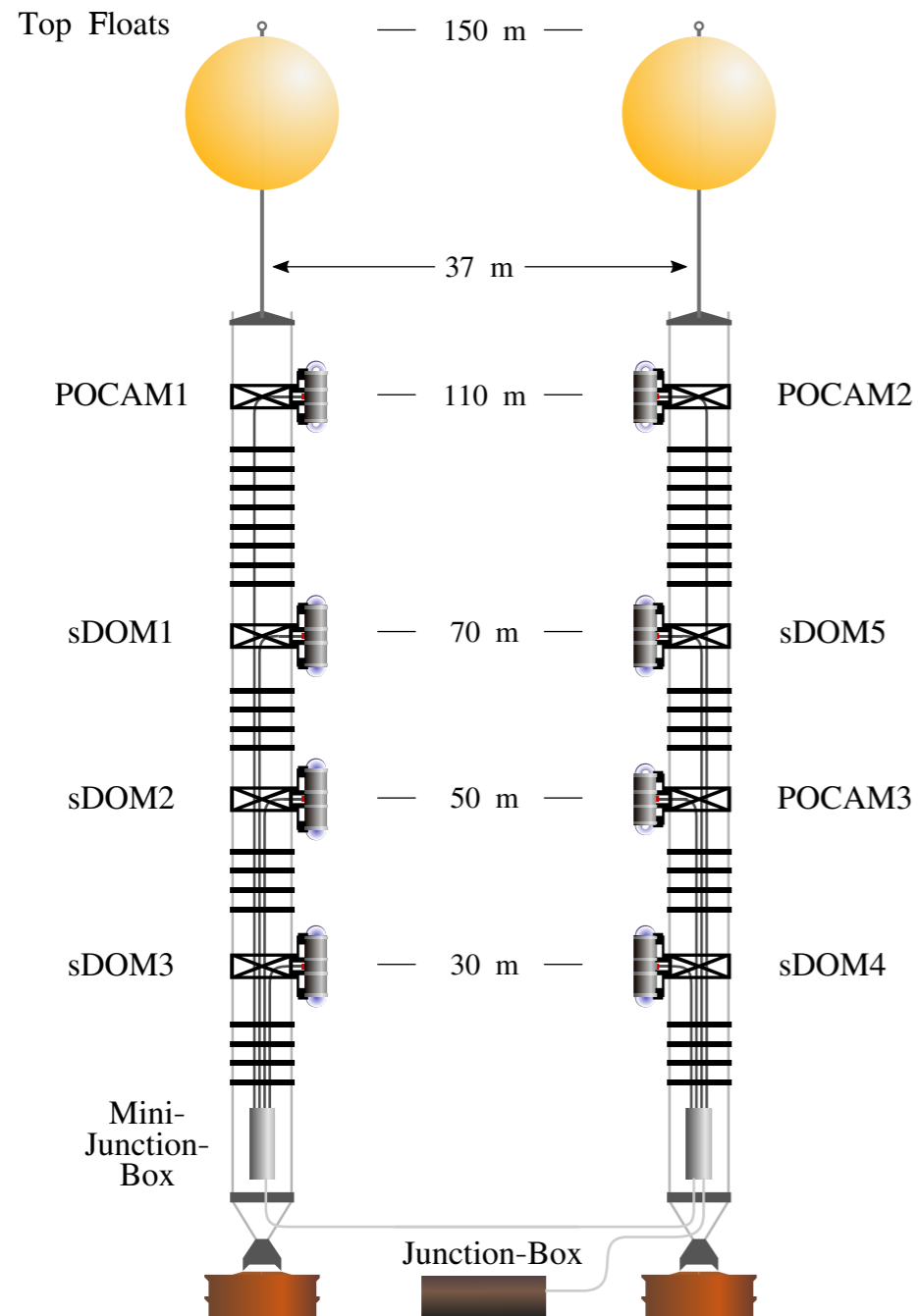
Cabled ocean observatory: North East Pacific Time-series Underwater Networked Experiment (NEPTUNE), completed in 2009, multidisciplinary subsea system.



P-ONE: PATHFINDER MISSIONS

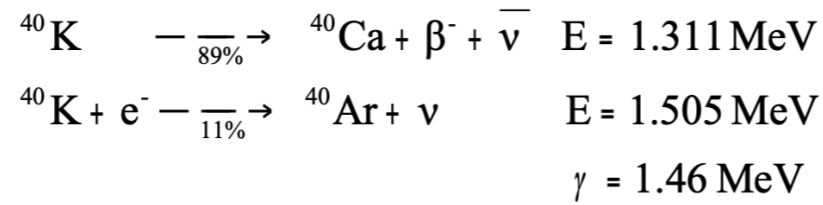
J. Bedard, E.R. et al., JINST (2019) - STRAW hardware

N. Bailly, E.R. et al., Eur. Phys. J. C (2021) - STRAW results



P-ONE: PATHFINDER MISSIONS

Result No.1: ^{40}K in situ measurement

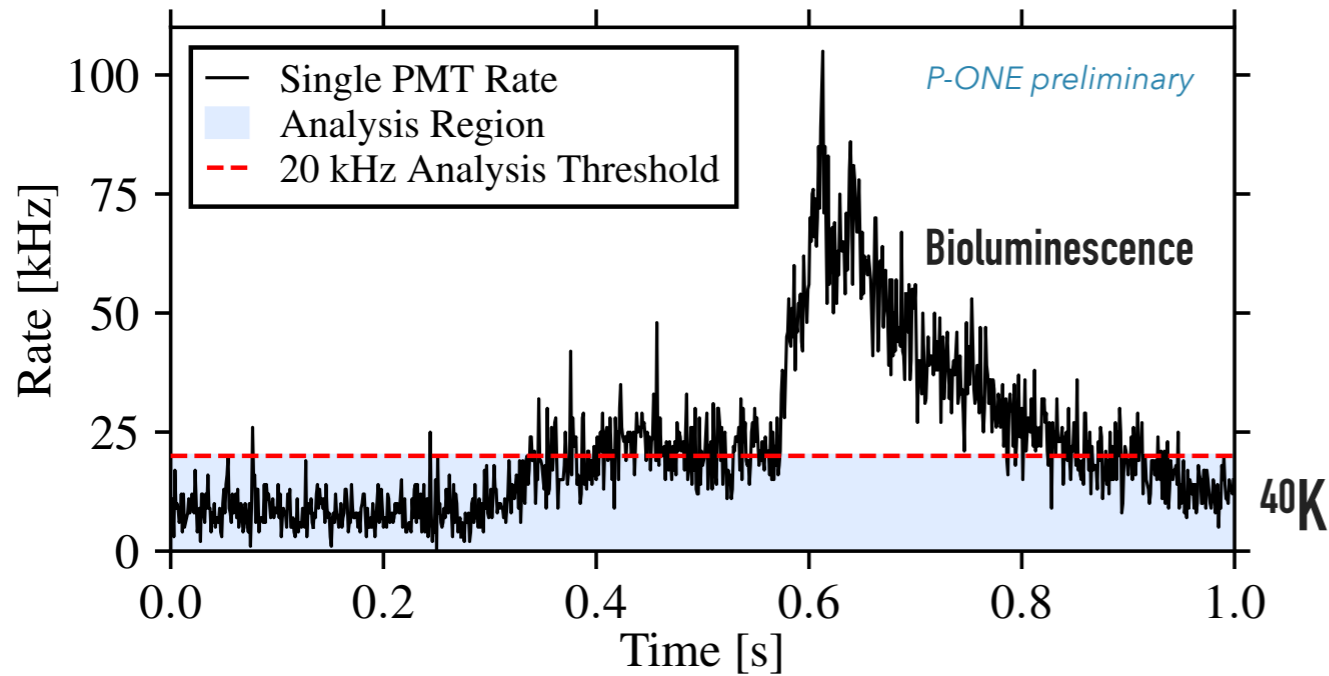


Long-term monitoring of the ANTARES optical module efficiencies using ^{40}K decays in sea water

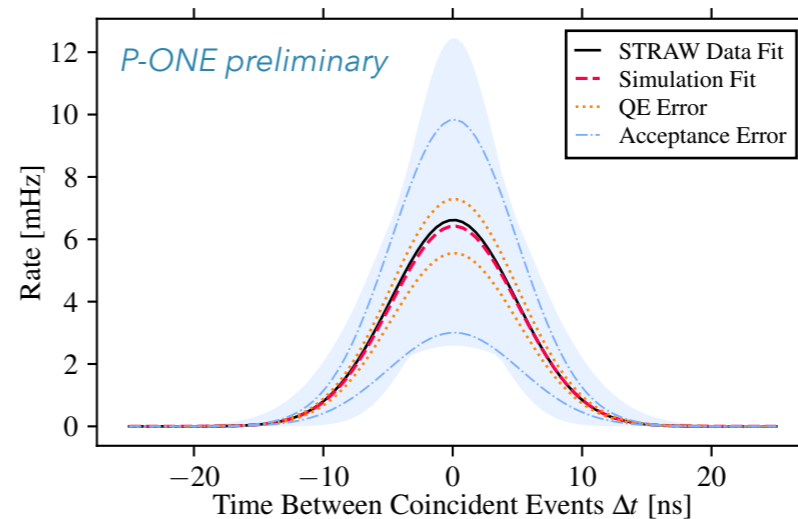
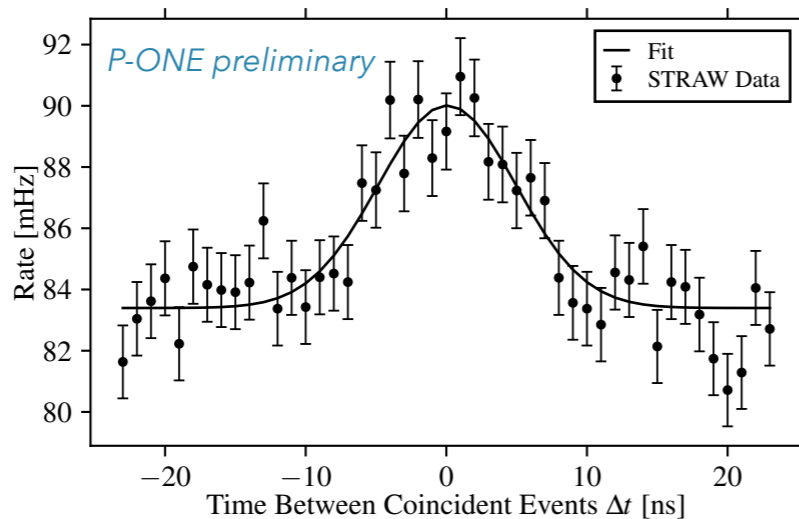
The ANTARES Collaboration

[A. Albert, M. André, \[...\] J. Zúñiga](#)

[The European Physical Journal C 78](#), Article number: 669 (2018) | [Cite this article](#)

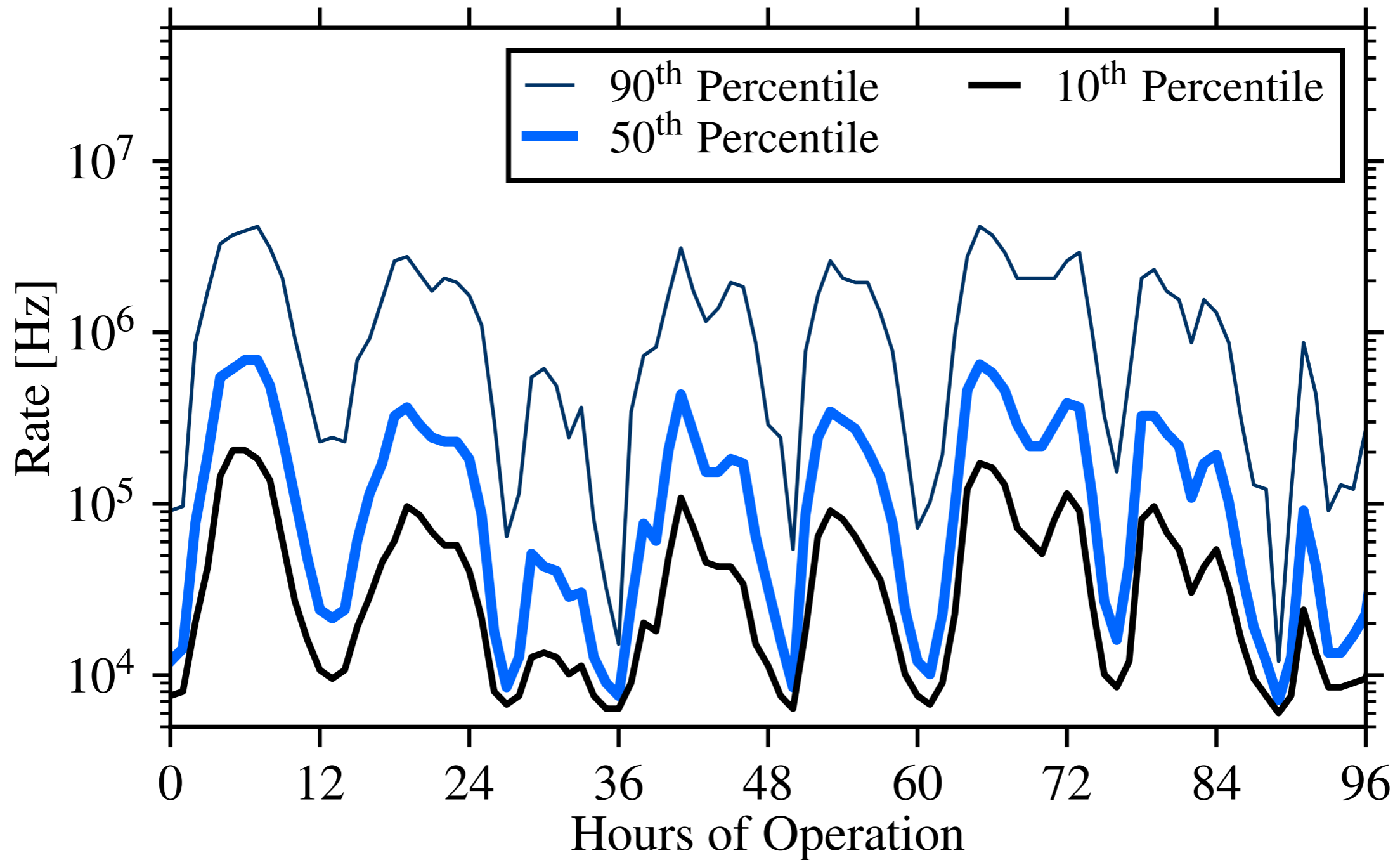


SALINITY FROM THIS WORK: $2.7 \pm 1.5\%$
 SALINITY FROM ONC: $3.482 \pm 0.001\%$
 SALINITY AT ANTARES SITE: 3.844%

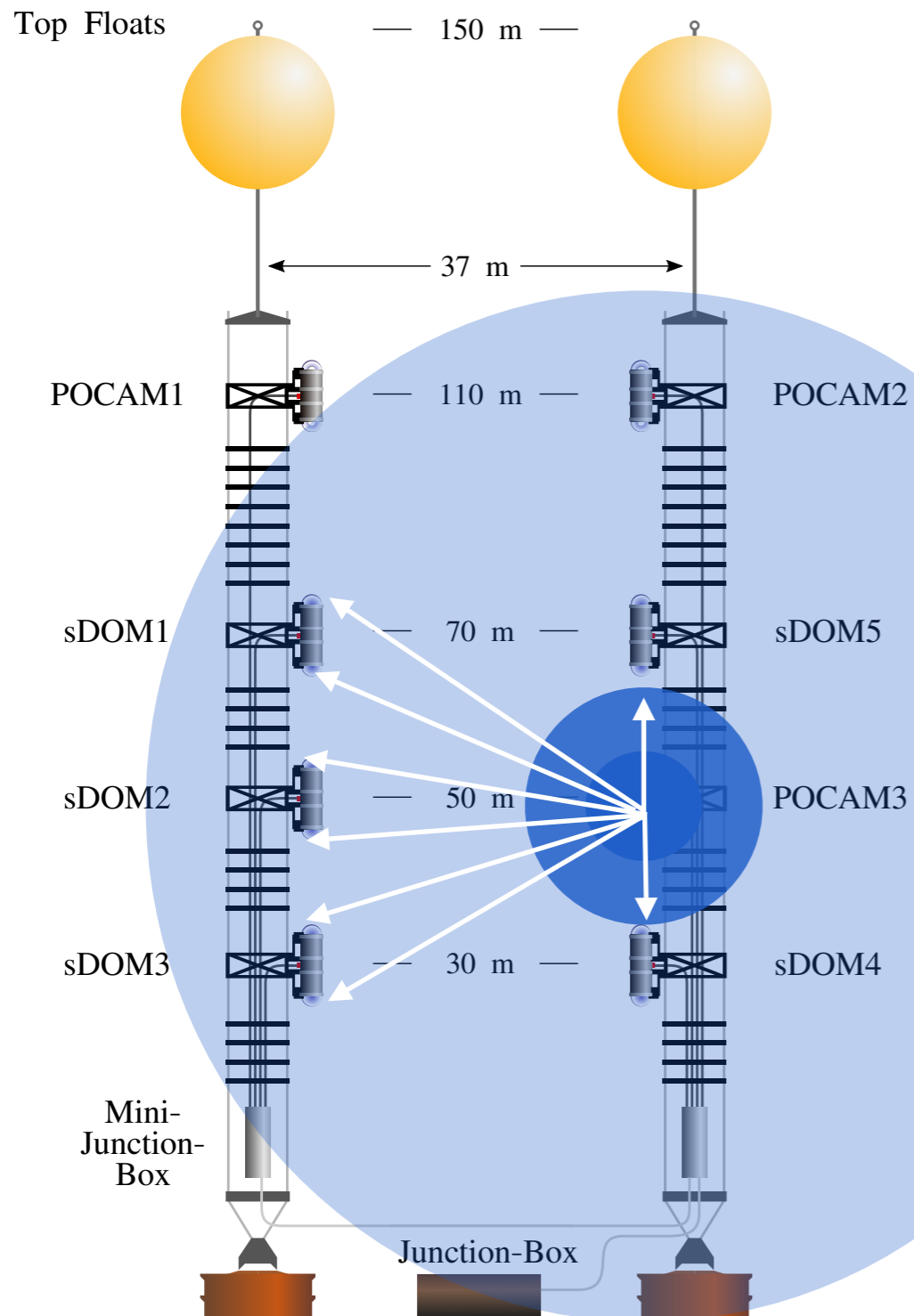


P-ONE: PATHFINDER MISSIONS

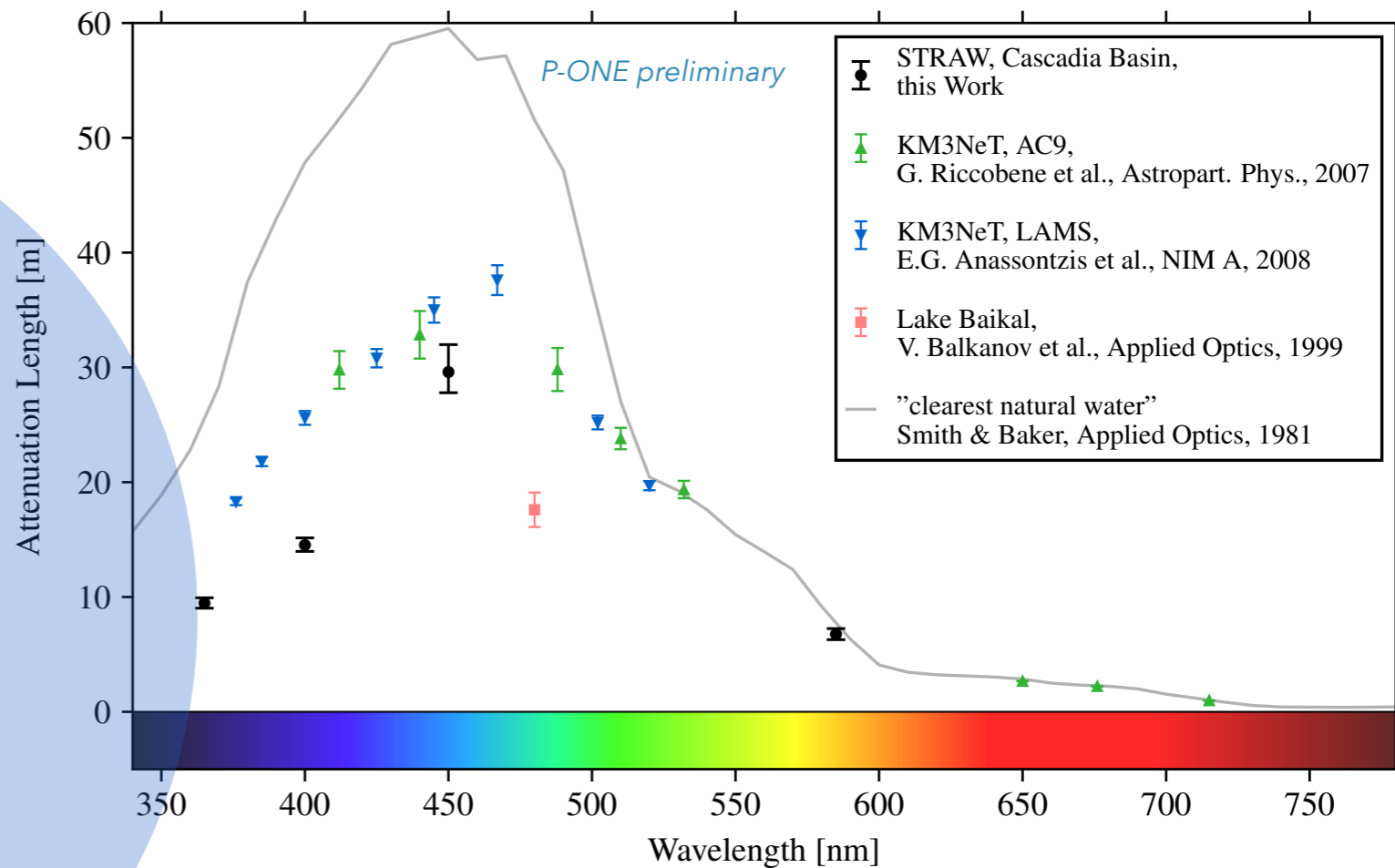
Result No.2: Bioluminescence



P-ONE: PATHFINDER MISSIONS



Result No.3: Attenuation length



P-ONE: THE PROTOTYPE PHASE

Target deployment: Spring 2024



SFB 1258

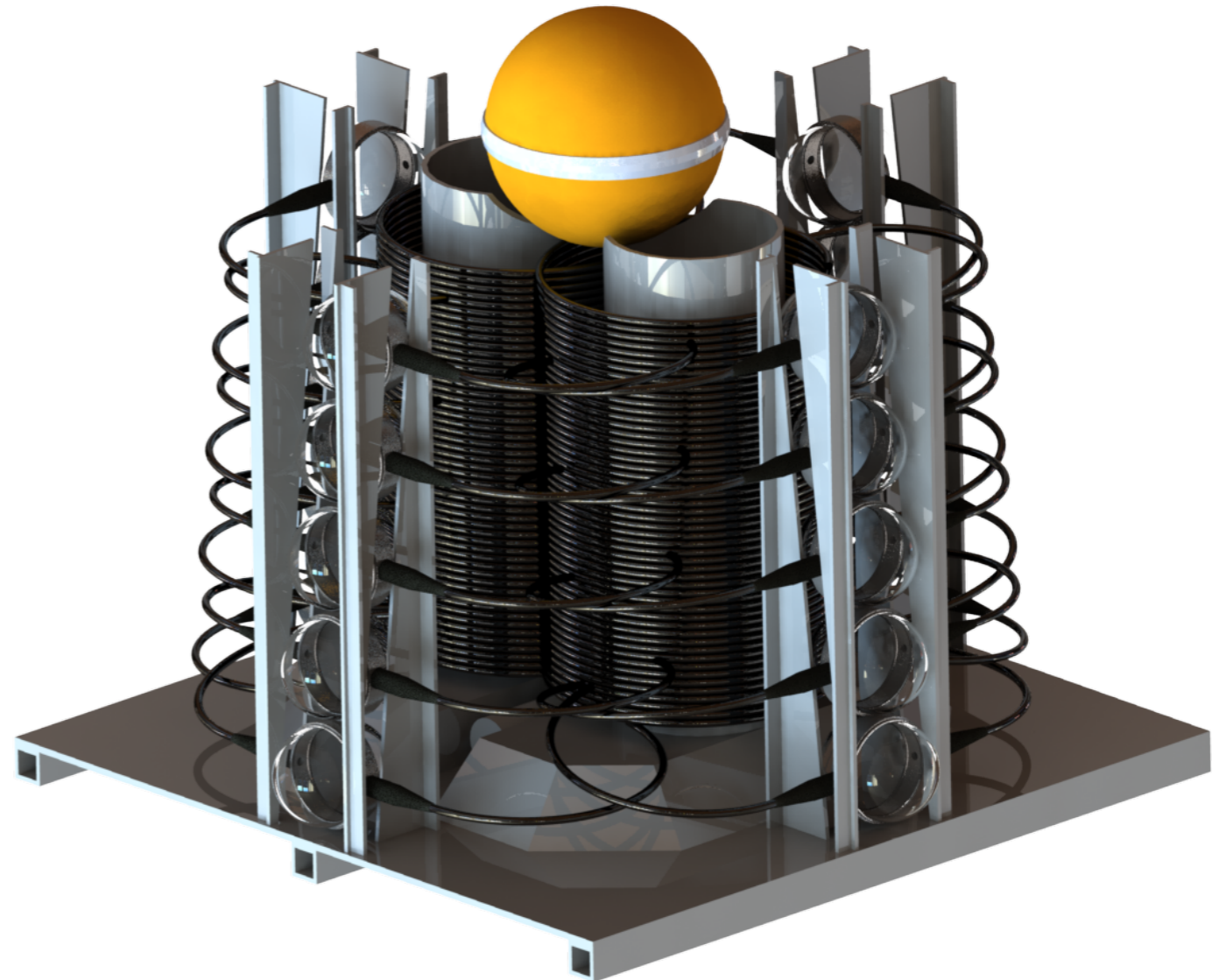
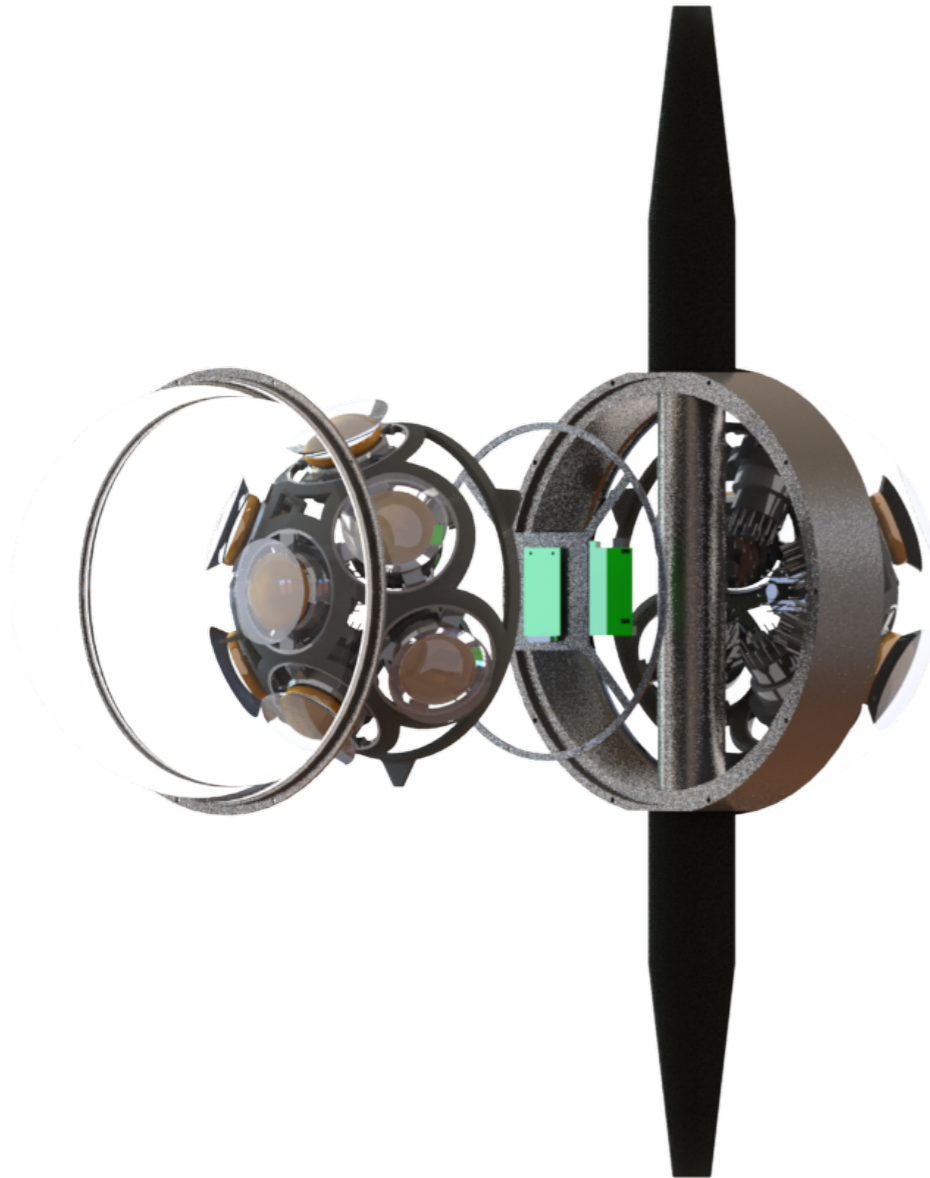
Neutrinos
Dark Matter
Messengers



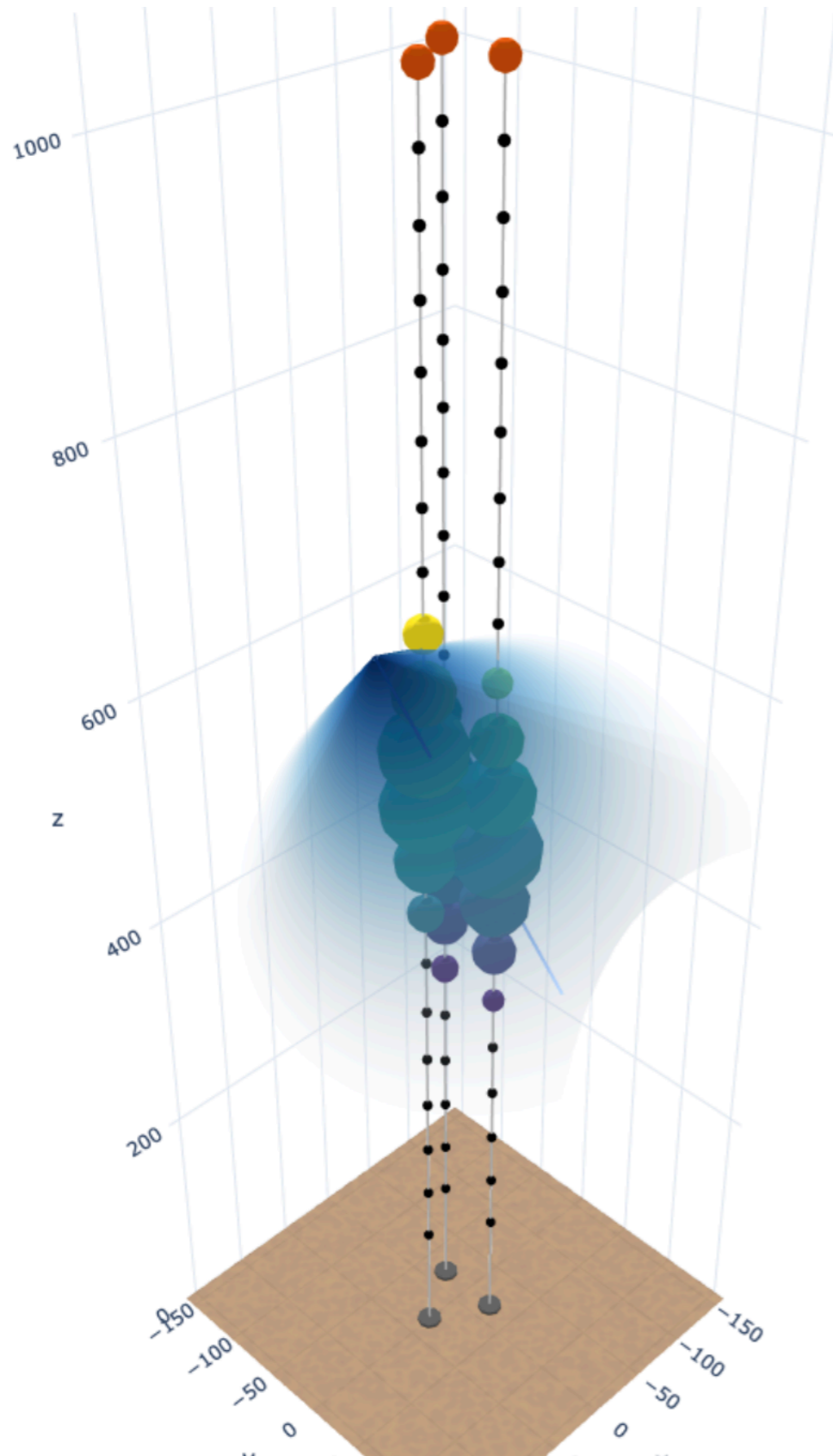
INNOVATION

Canada Foundation
for Innovation

Fondation canadienne
pour l'innovation



P-ONE: THE FIRST SECTOR OF 3 LINES



European Research Council

Established by the European Commission

FIRST neutrinos in the Pacific Ocean - Scale it Up!
P-ONE & Planetary Network of Neutrino Telescopes.

ON THE ICECUBE SIDE: UPGRADE AND GEN2

UNDER DESIGN

EXISTING

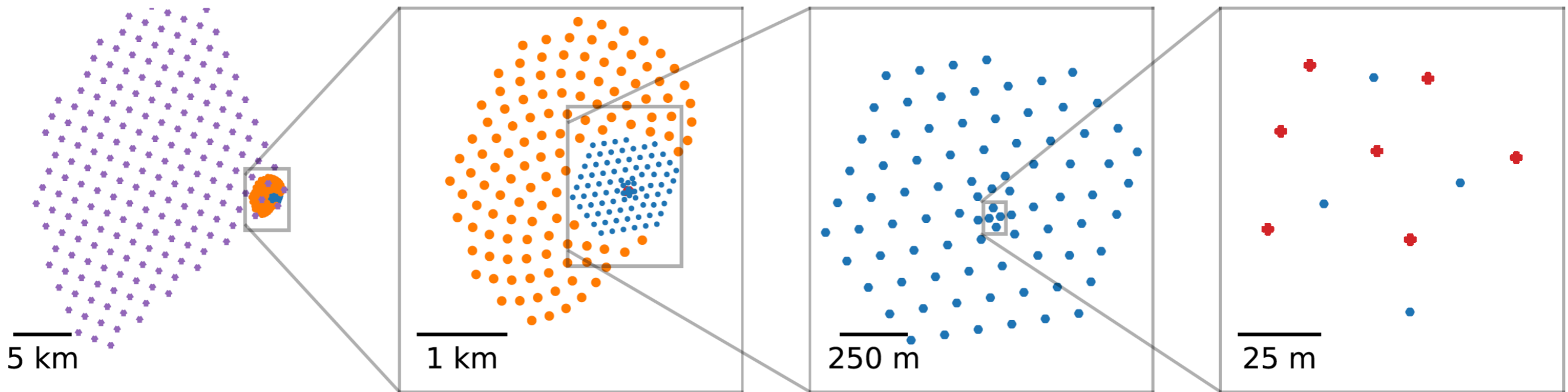
APPROVED

Gen2-Radio

IceCube-Gen2

IceCube

IceCube Upgrade



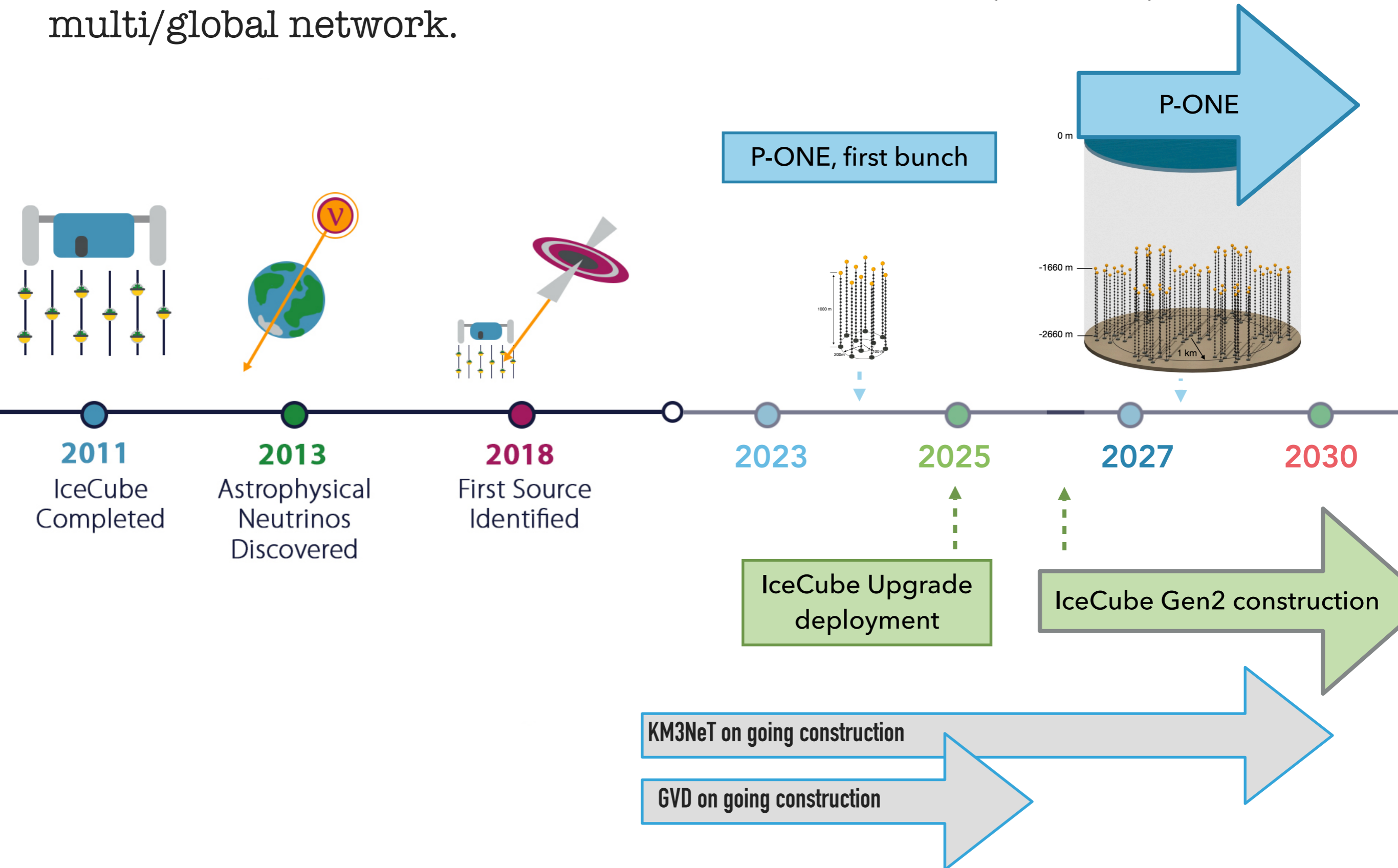
10 PeV

10 TeV

1 TeV

few GeV

The decadal vision: from the single site telescope (IceCube) to the multi/global network.



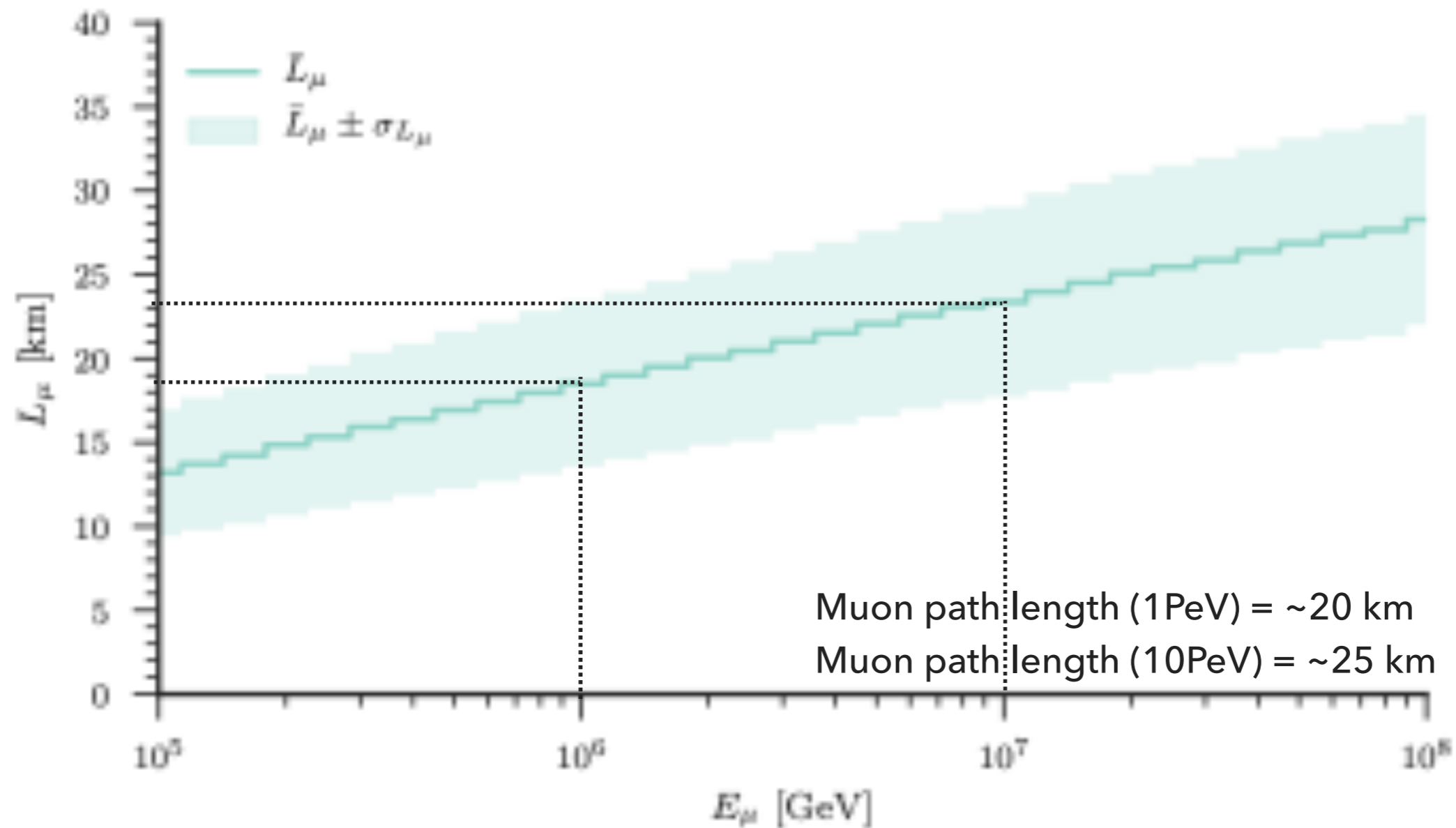
OUTLOOK

- IceCube has been pioneering the exploration of the universe with high-energy neutrinos.
- Milestones achieved, exciting progress ahead: stay tuned!!
- Need of more and larger neutrino telescopes around the planet Earth to cover the sky and boost the discovery potential.
- PLEnuM effort:
 - With 3 x IceCube in the North, overall improvement by a factor of 10-100
 - New collaboration established with Ocean Networks Canada for the *Pacific Ocean Neutrino Experiment (P-ONE)*: pathfinder mission completed, prototype phase started, first sector financed!
- A path forward for IceCube-Gen2 in preparation.



NEUTRINO INTERACTION CHANNEL - MUON TRACKS

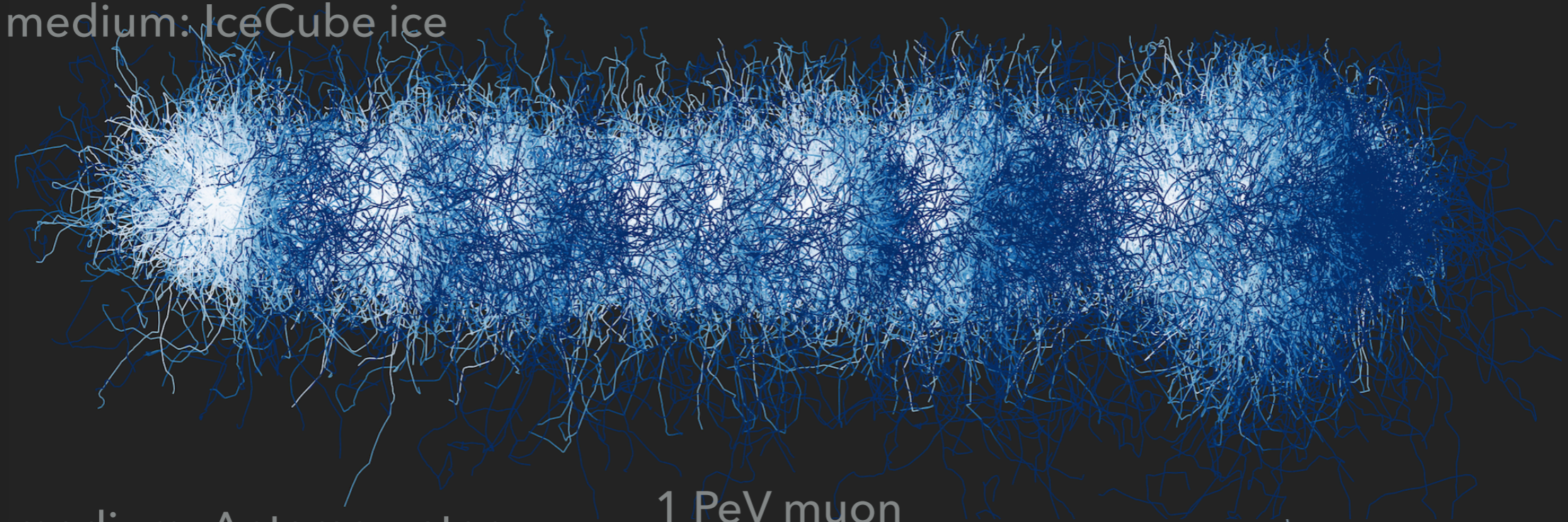
➔ **~1KM: SHORT FOR HIGH ENERGY MUONS**



NEW ENTRY ON THE NEUTRINO MAP - PLENUM@ONC

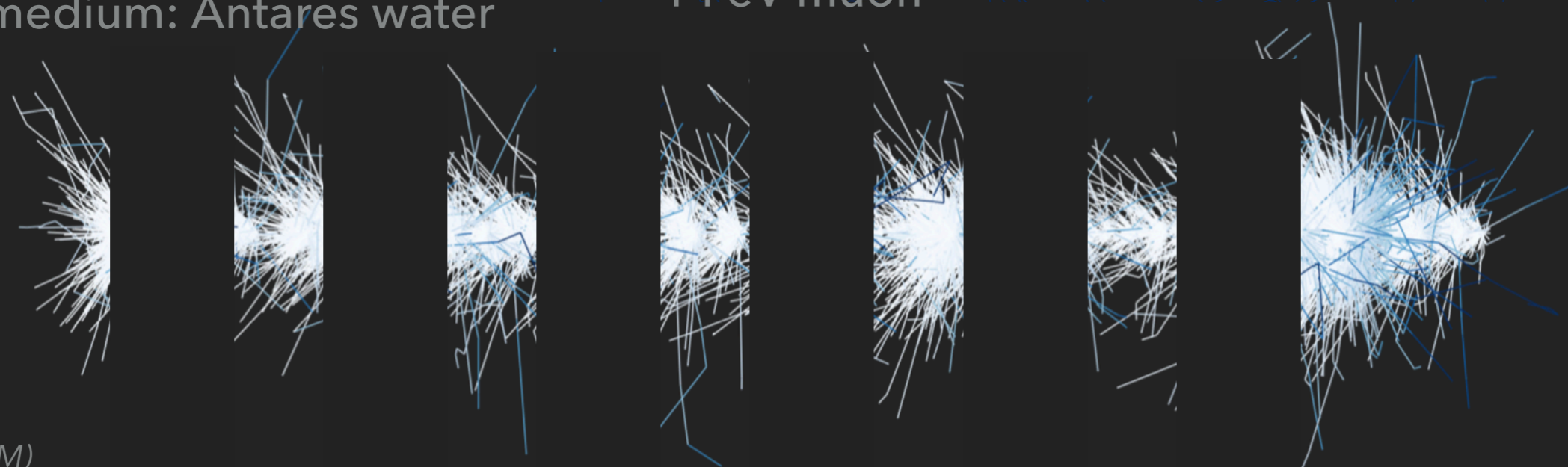
BRAINSTORMING AROUND A SEGMENTED DETECTOR FOR HE HORIZONTAL TRACKS

medium: IceCube ice



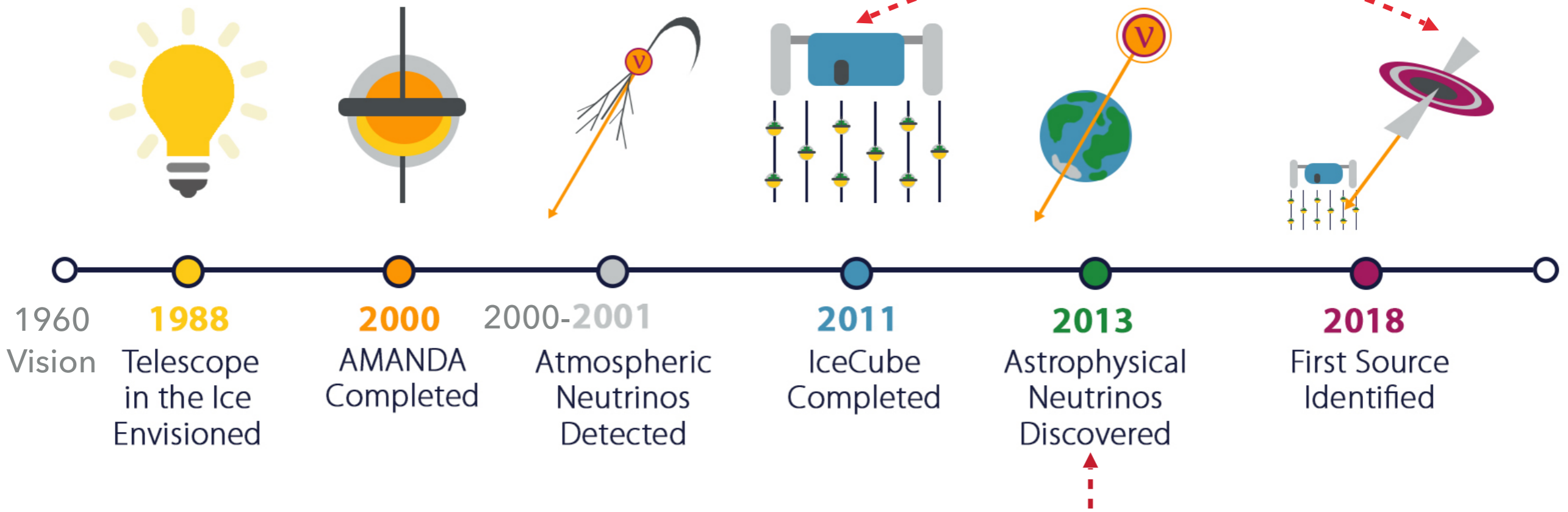
medium: Antares water

1 PeV muon



A History of Neutrino Astronomy in Antarctica

IceCube and MM partners *first* association to a source

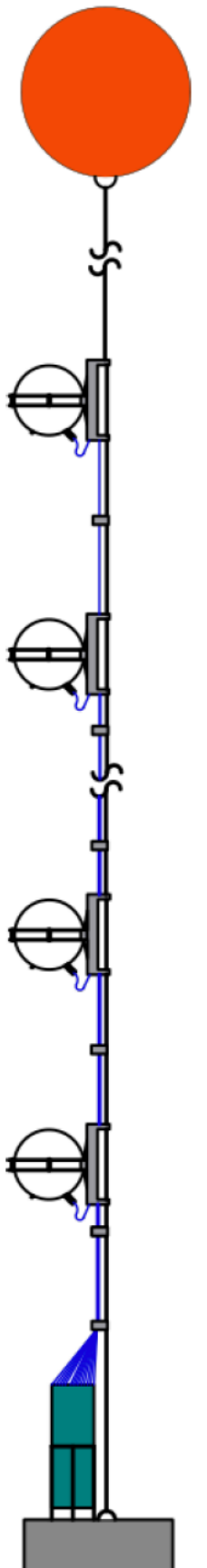


IceCube discovery of *diffuse* astrophysics neutrinos



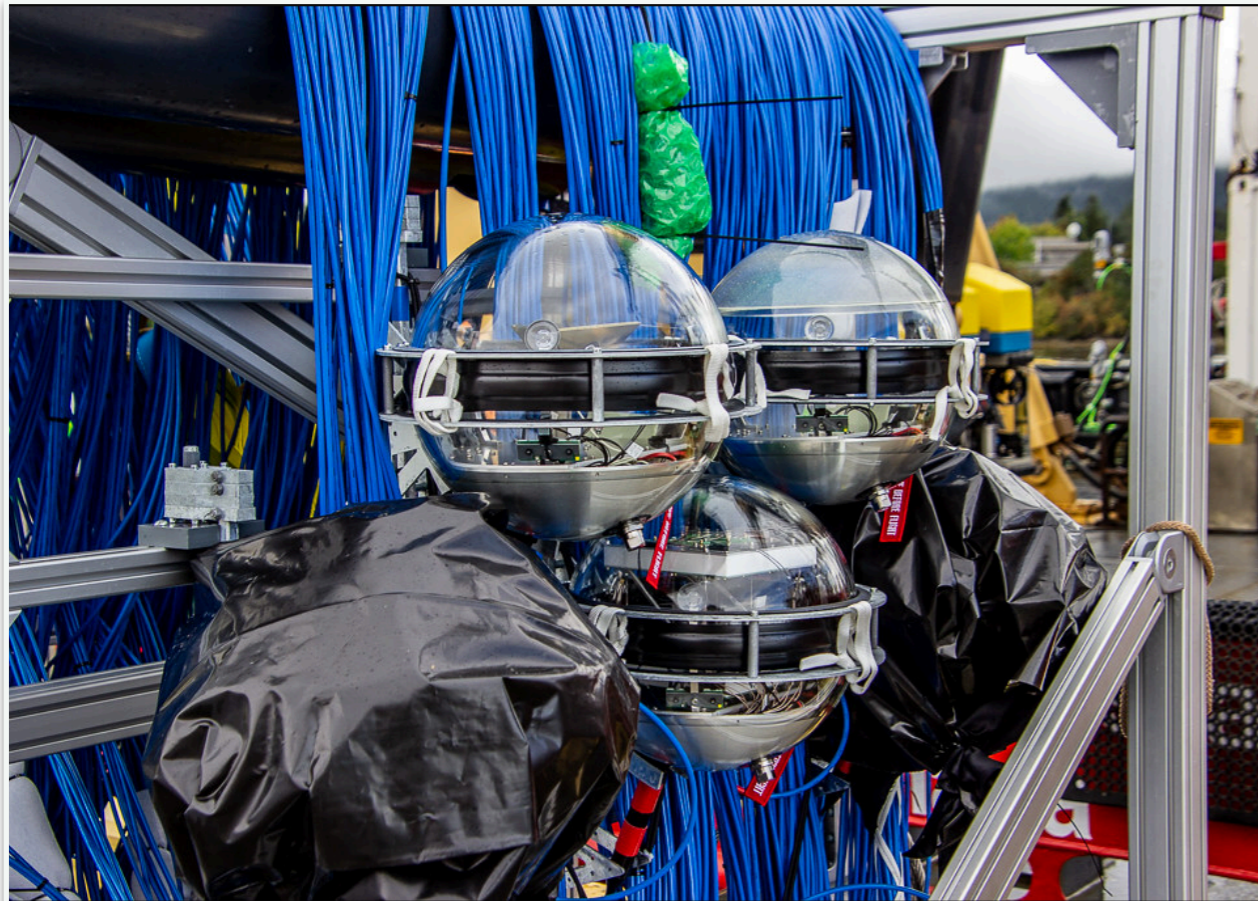
PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE) STRAW-B PATHFINDER II: DEPLOYED IN OCTOBER 2020

Test longer mooring (500m) and specialised devices. Complete qualification of the deep site.



PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE) STRAW-B PATHFINDER II: DEPLOYED IN OCTOBER 2020

Test longer mooring (500m) and specialised devices. Complete qualification of the deep site.



PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE)

STRAW-B PATHFINDER II: DEPLOYED IN OCTOBER 2020

Test longer mooring (500m) and specialised devices. Complete qualification of the deep site.

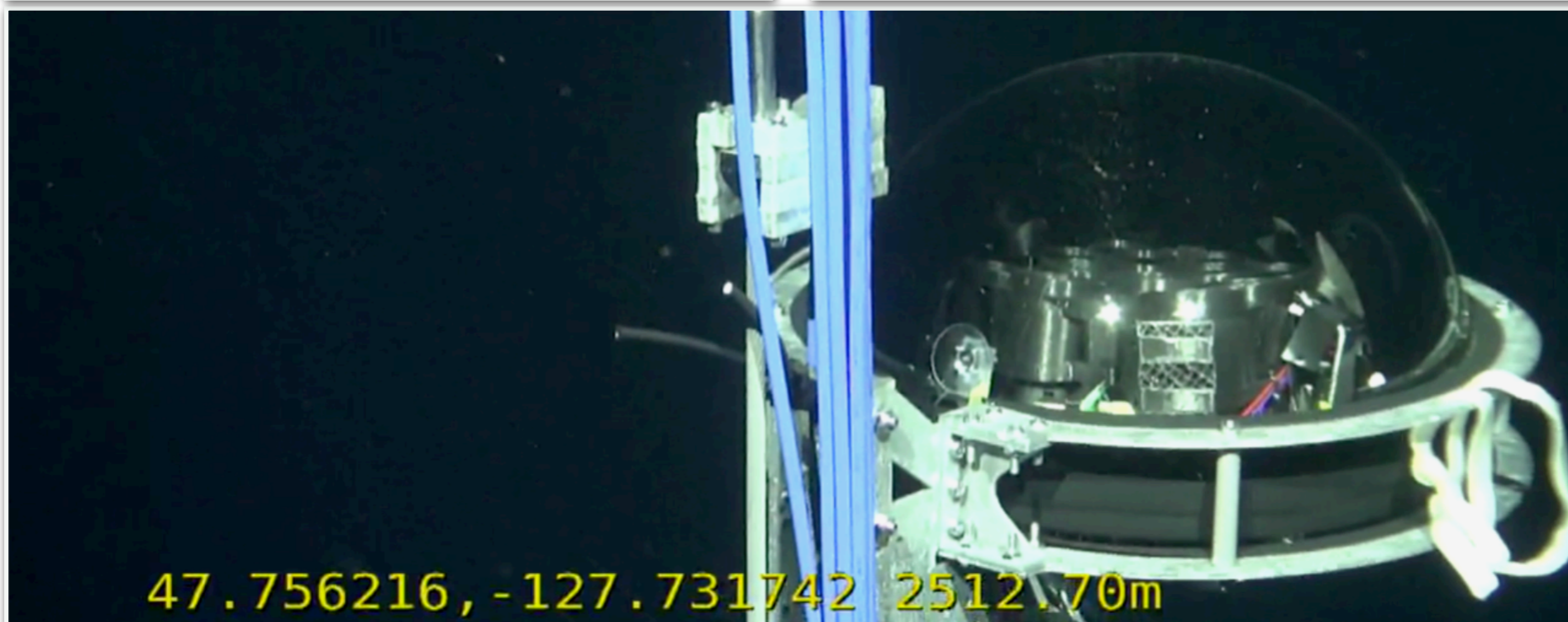
@ONC



@TUM



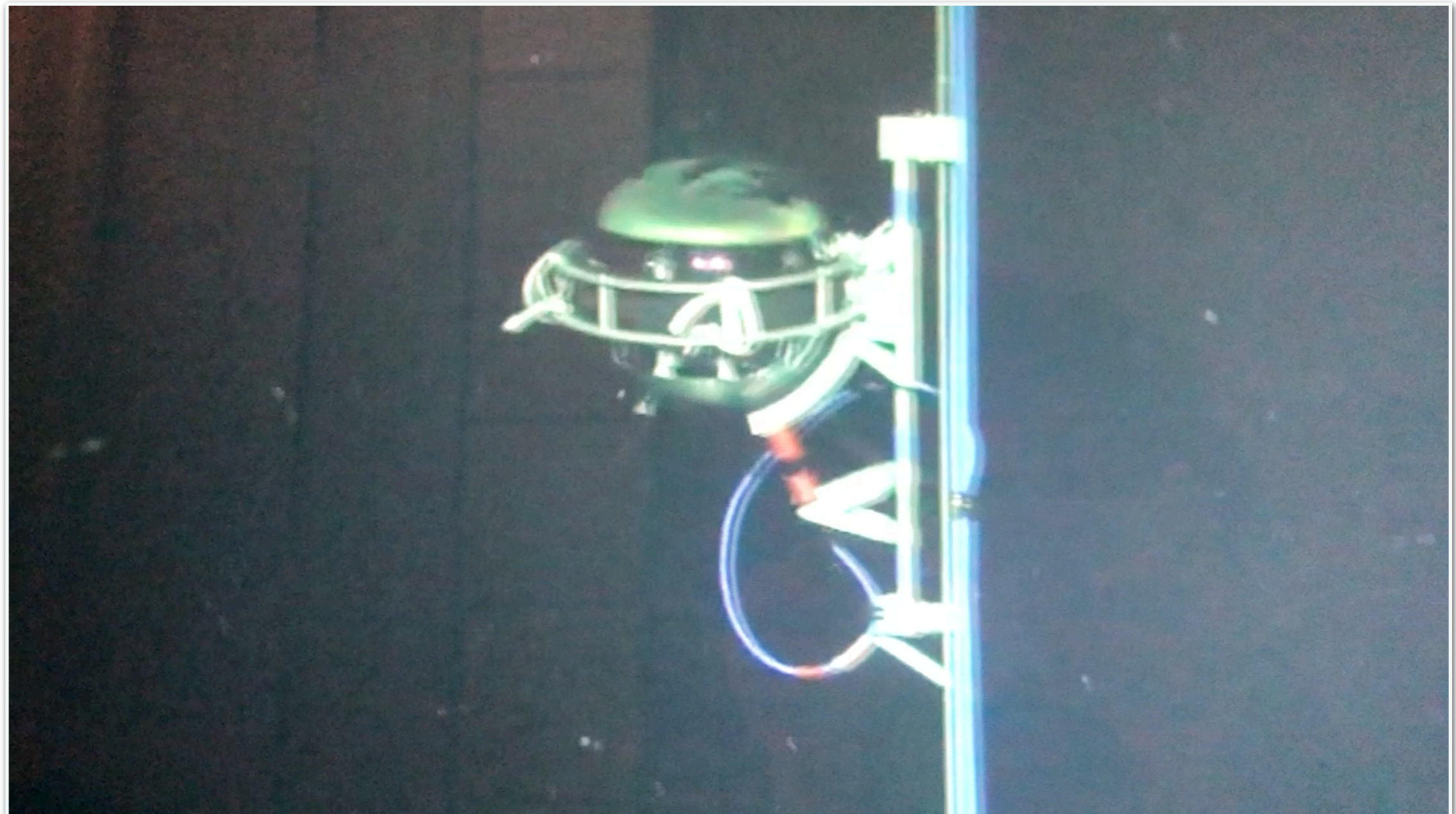
@Cascadia Basin,
-2600m



47.756216, -127.731742 2512.70m

PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE) STRAW-B PATHFINDER II: DEPLOYED IN OCTOBER 2020

Test longer mooring (500m) and specialised devices. Complete qualification of the dee



PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE)

STRAW-B PATHFINDER II: DEPLOYED IN OCTOBER 2020

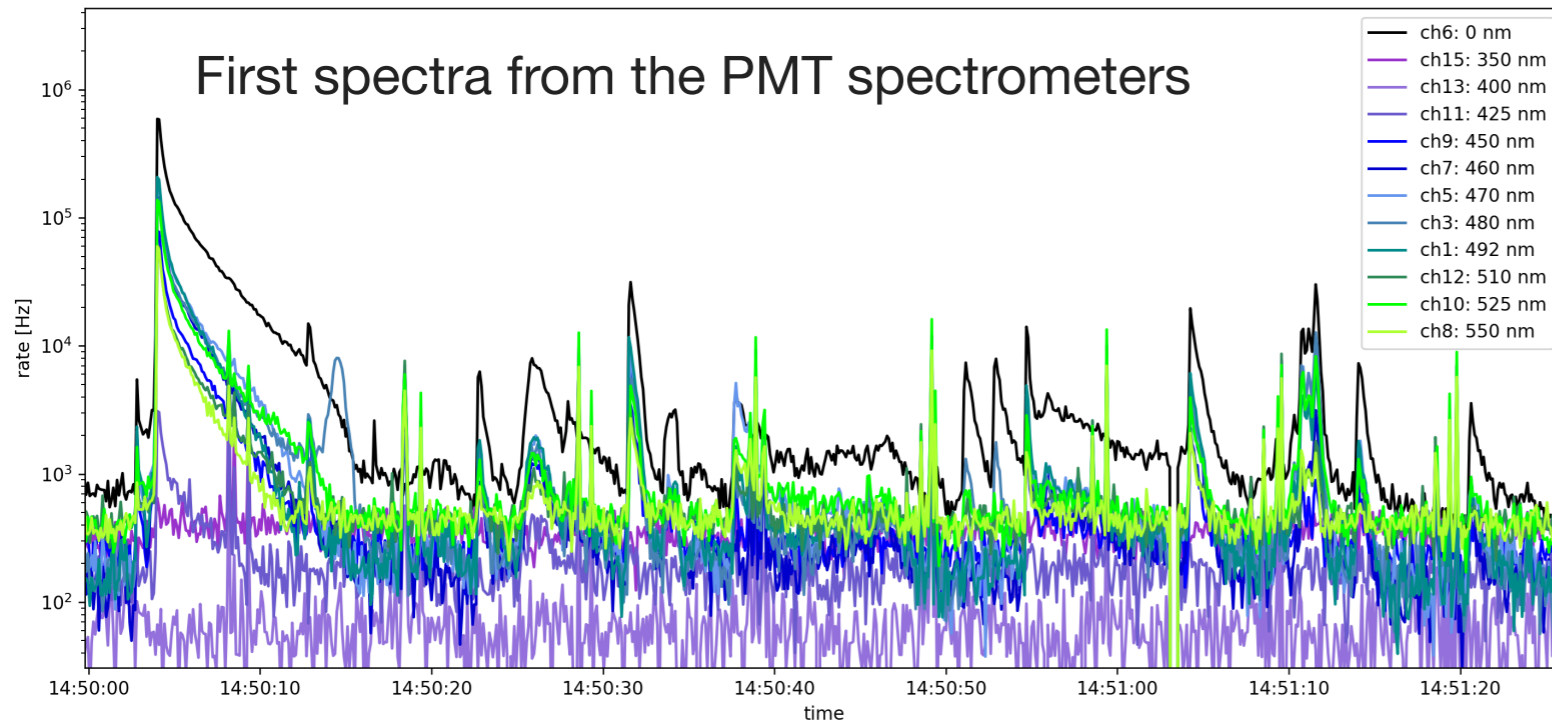
ONC plotting utility (DAQ current, temp., hum.)



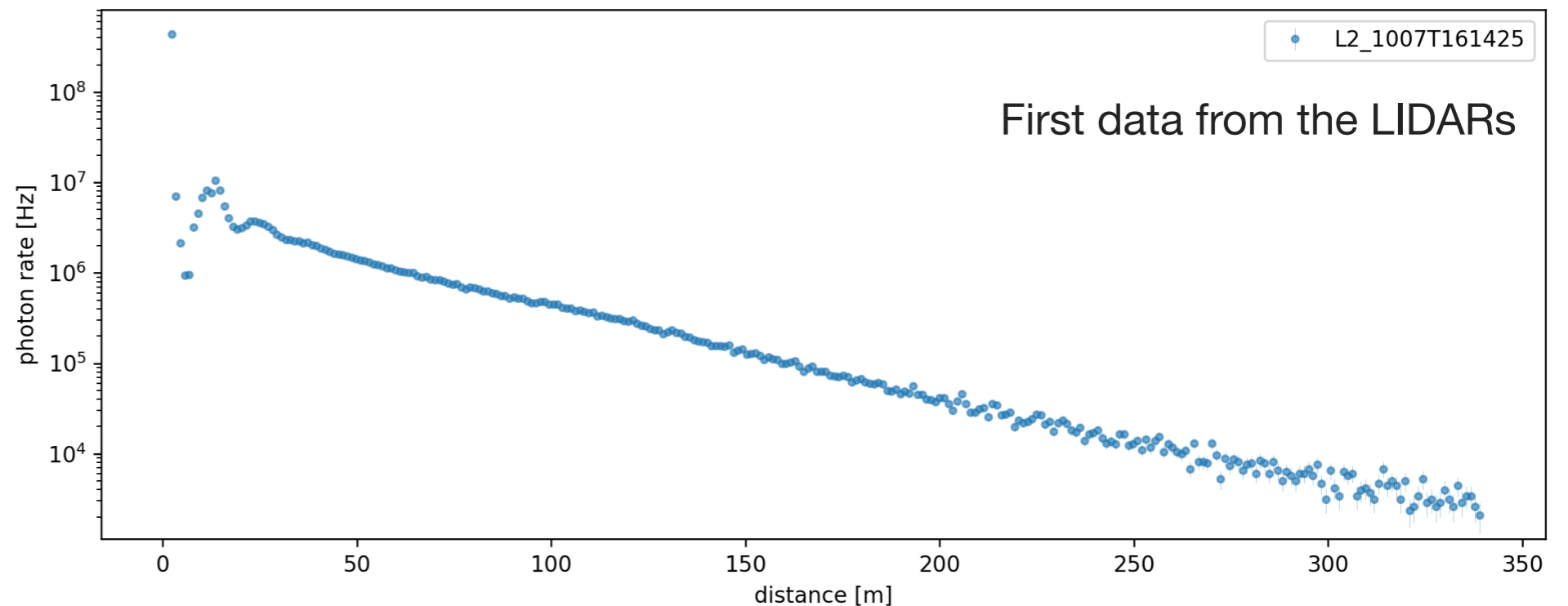
One module over ten did not survive the deployment, investigation on-going.

PACIFIC OCEAN NEUTRINO EXPERIMENT (P-ONE)

STRAW-B PATHFINDER II: DEPLOYED IN OCTOBER 2020



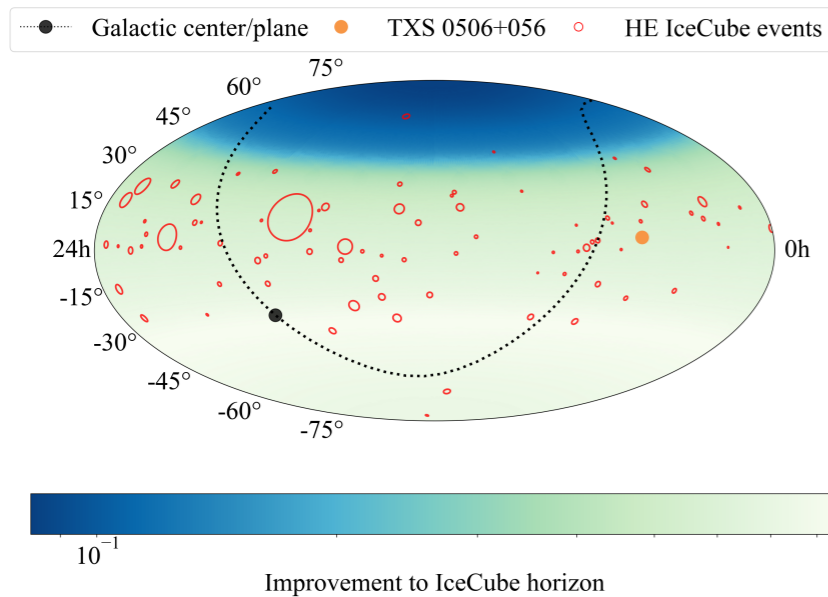
Work in progress



PLE_vM

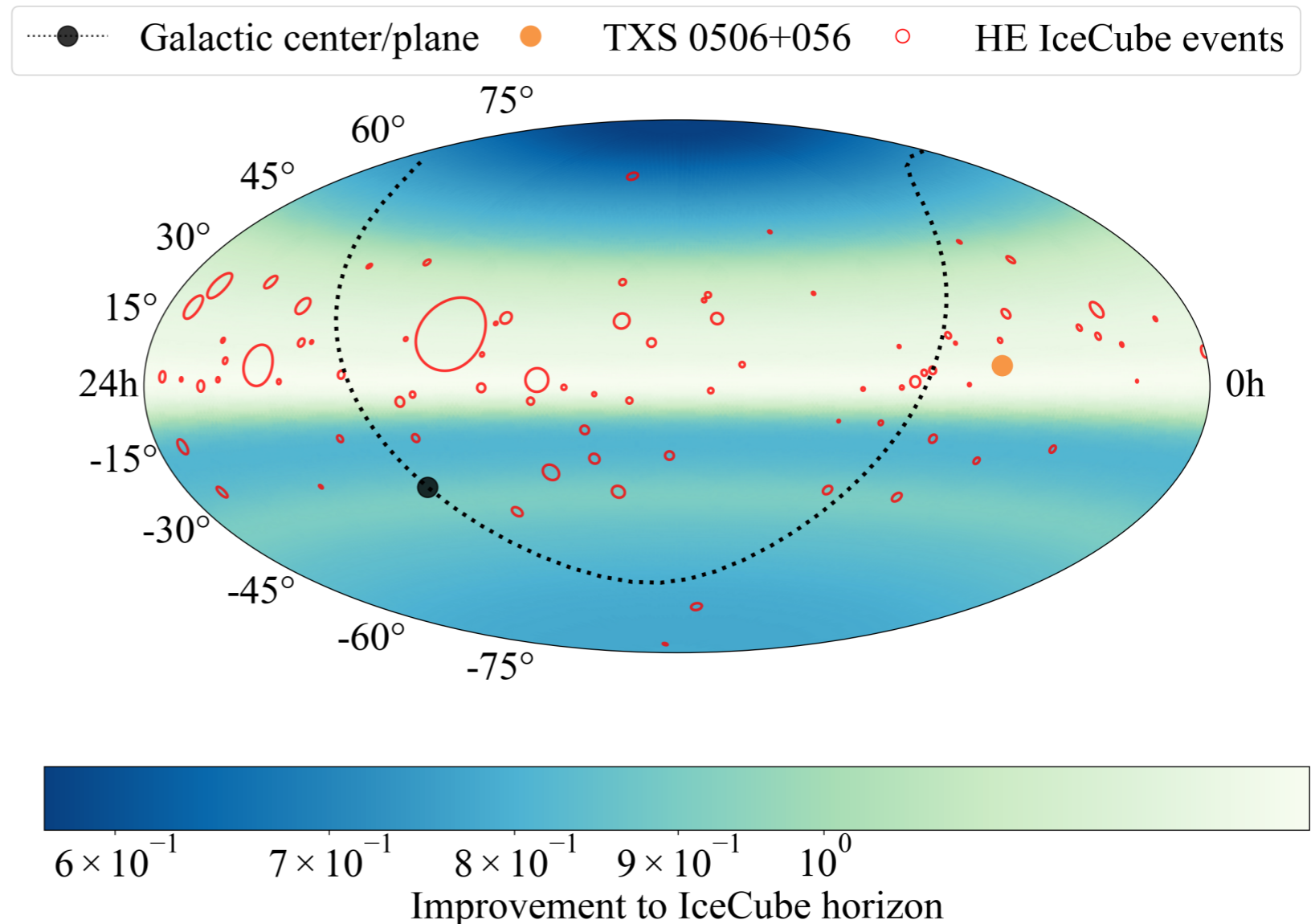
ICECUBE & BAIKAL (OR ANOTHER SINGLE SITE IN THE NORTH)

➔ RELATIVE IMPROVEMENT VS ICECUBE HORIZON BEST SENSITIVITY



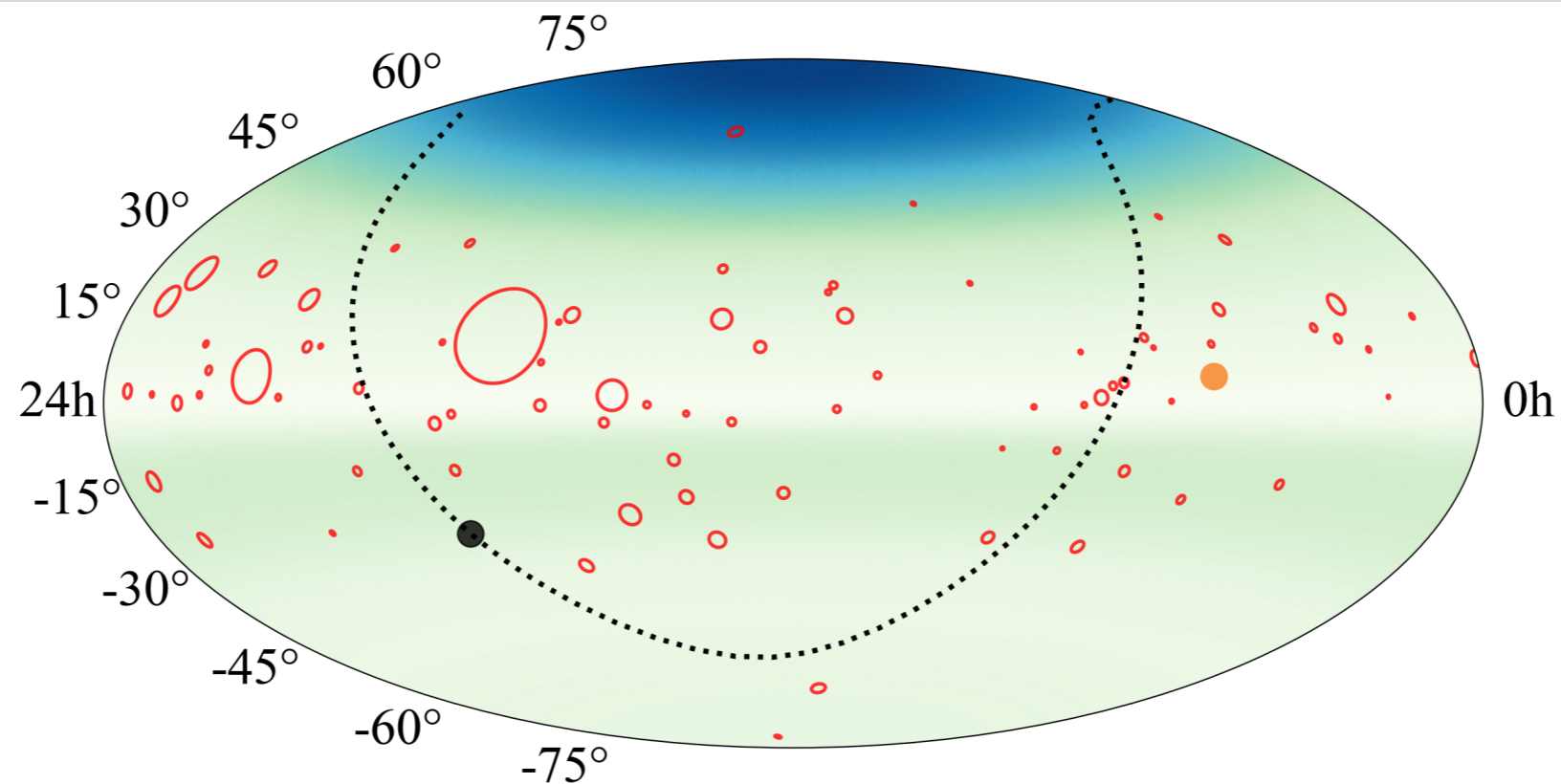
GVD only

GVD+IceCube / IceCube horizon



PLE_vM

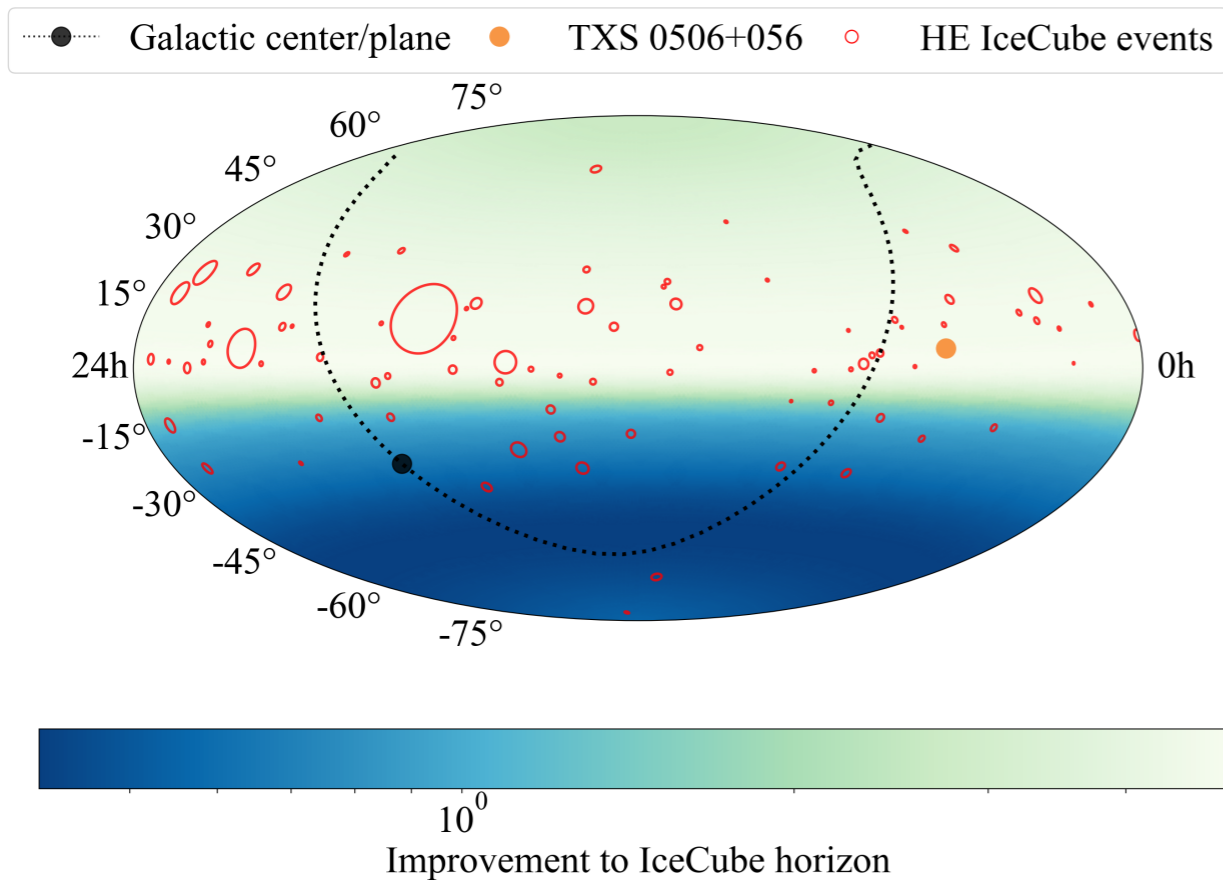
ICECUBE & BAIKAL & CAPO PASSERO & OCEAN NETWORK CANADA

➔ **RELATIVE IMPROVEMENT VS ICECUBE HORIZON BEST SENSITIVITY**

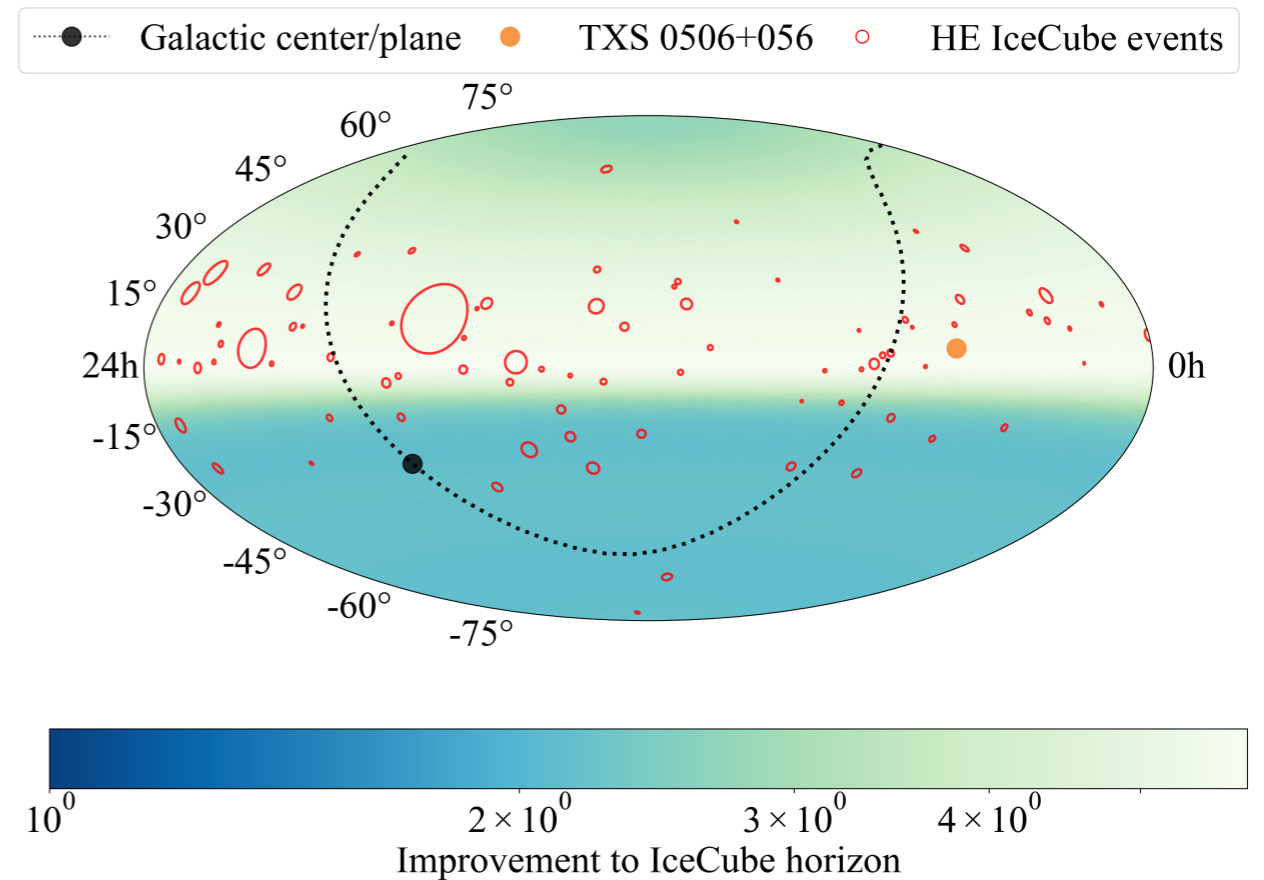
PLEνM

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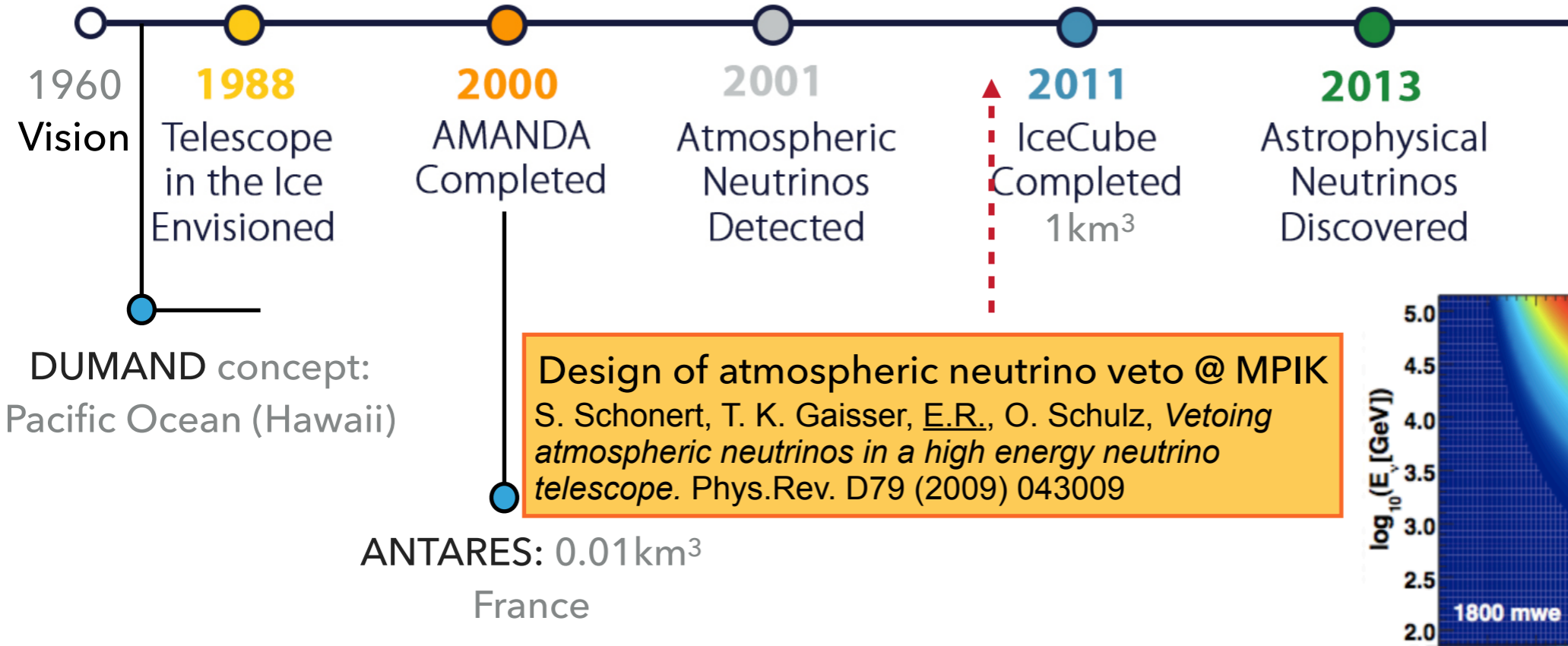
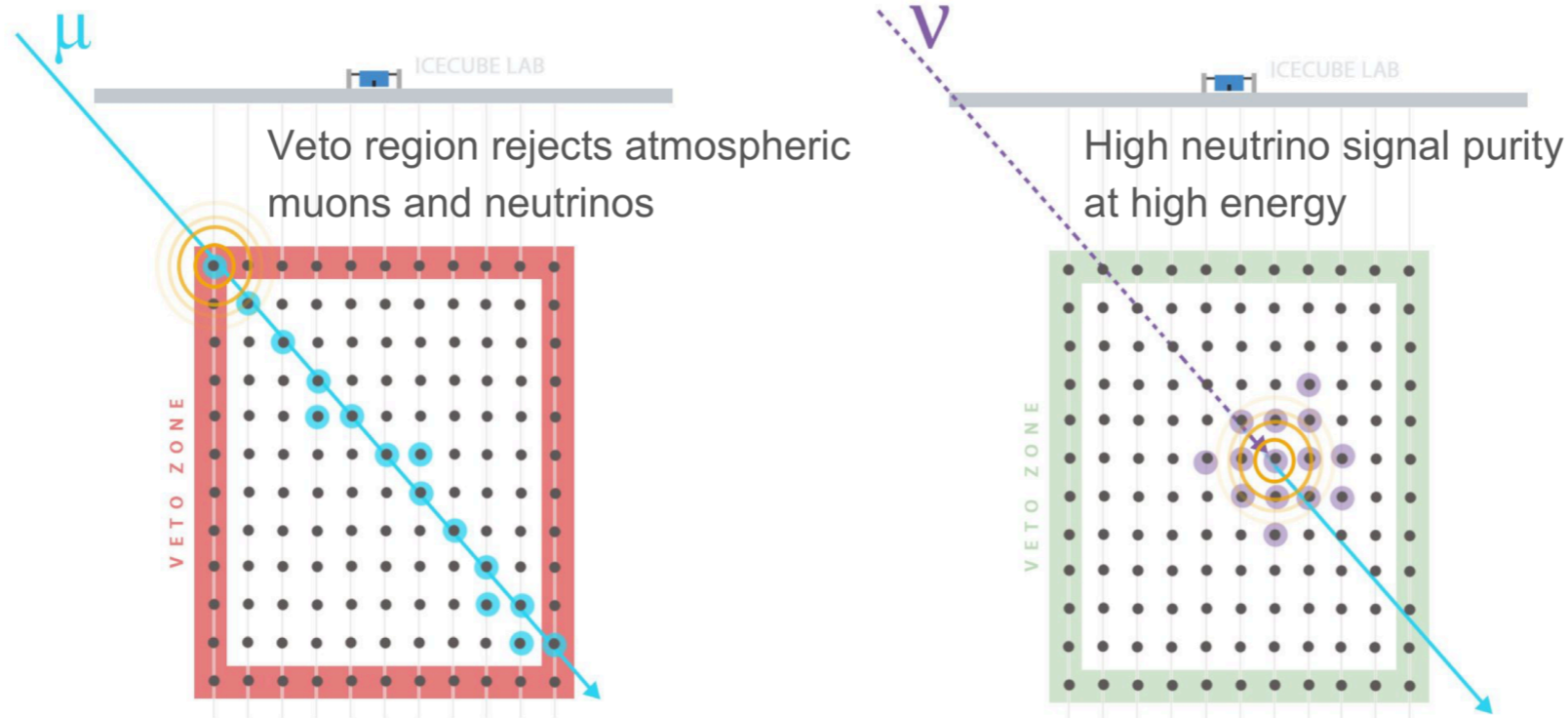
IceCube vs Gen2



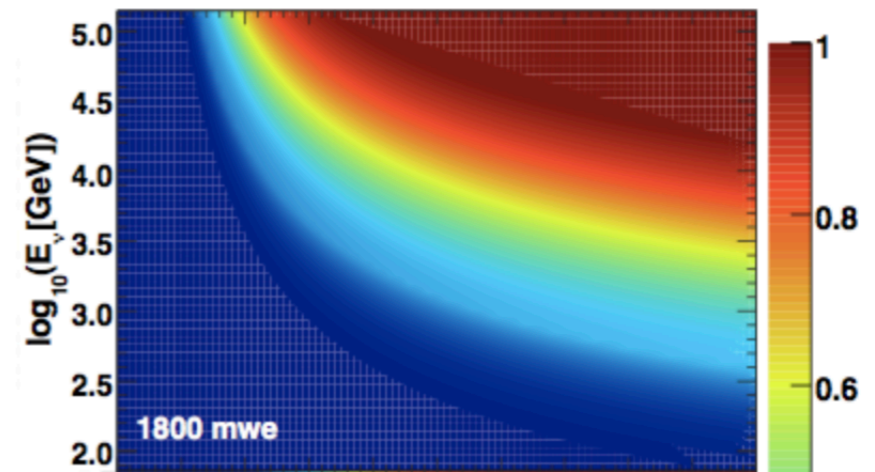
IceCube vs Gen2+GVD+KM3NeT+ONC



Starting Events



Design of atmospheric neutrino veto @ MPIK
 S. Schonert, T. K. Gaisser, E.R., O. Schulz, *Vetoing atmospheric neutrinos in a high energy neutrino telescope*. Phys.Rev. D79 (2009) 043009



What do we need in order to open the cosmic neutrino sky to more *routine* observations?



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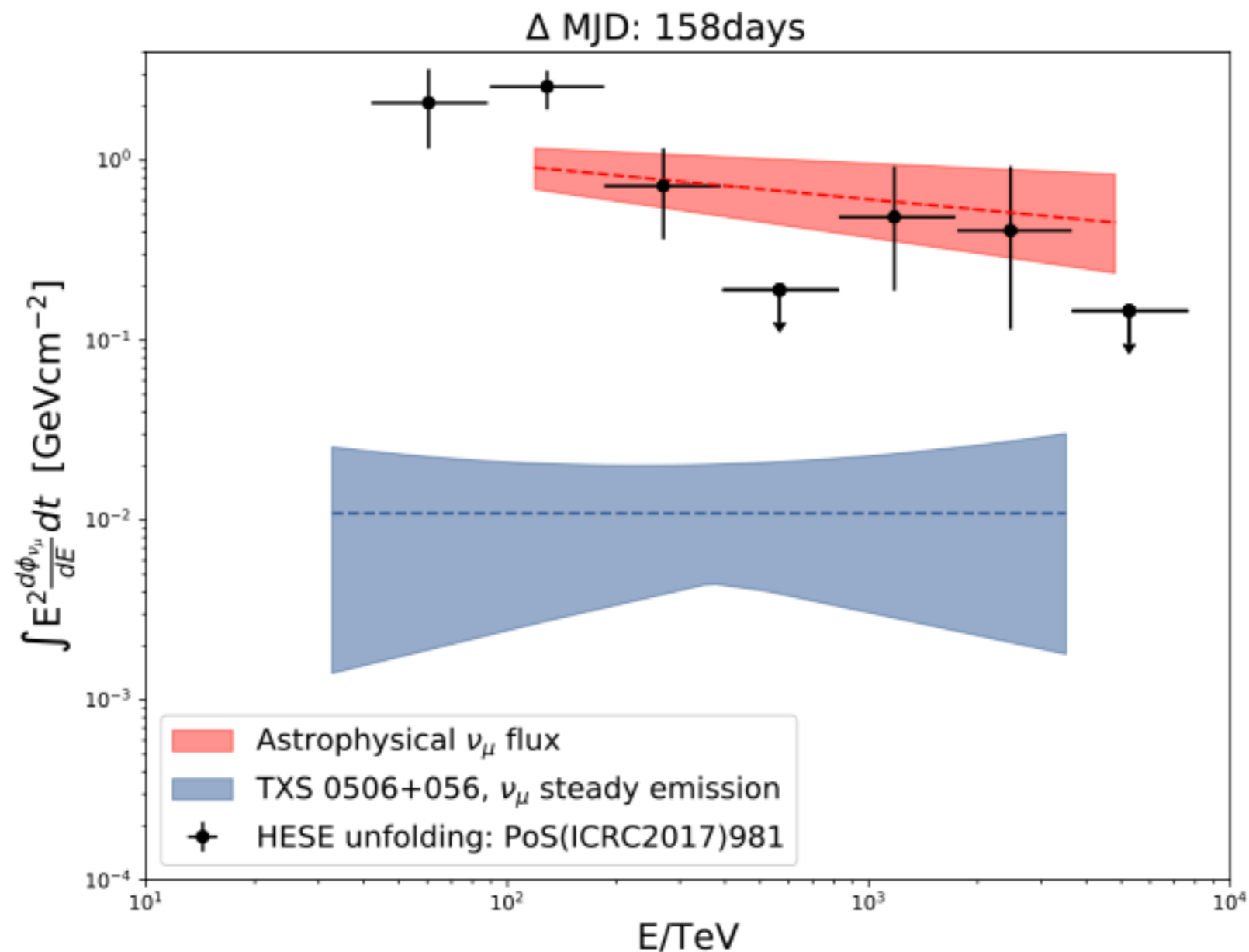
More OBSERVERS



THE AFTERMATH OF TXS 0506+056: IS A BLAZAR

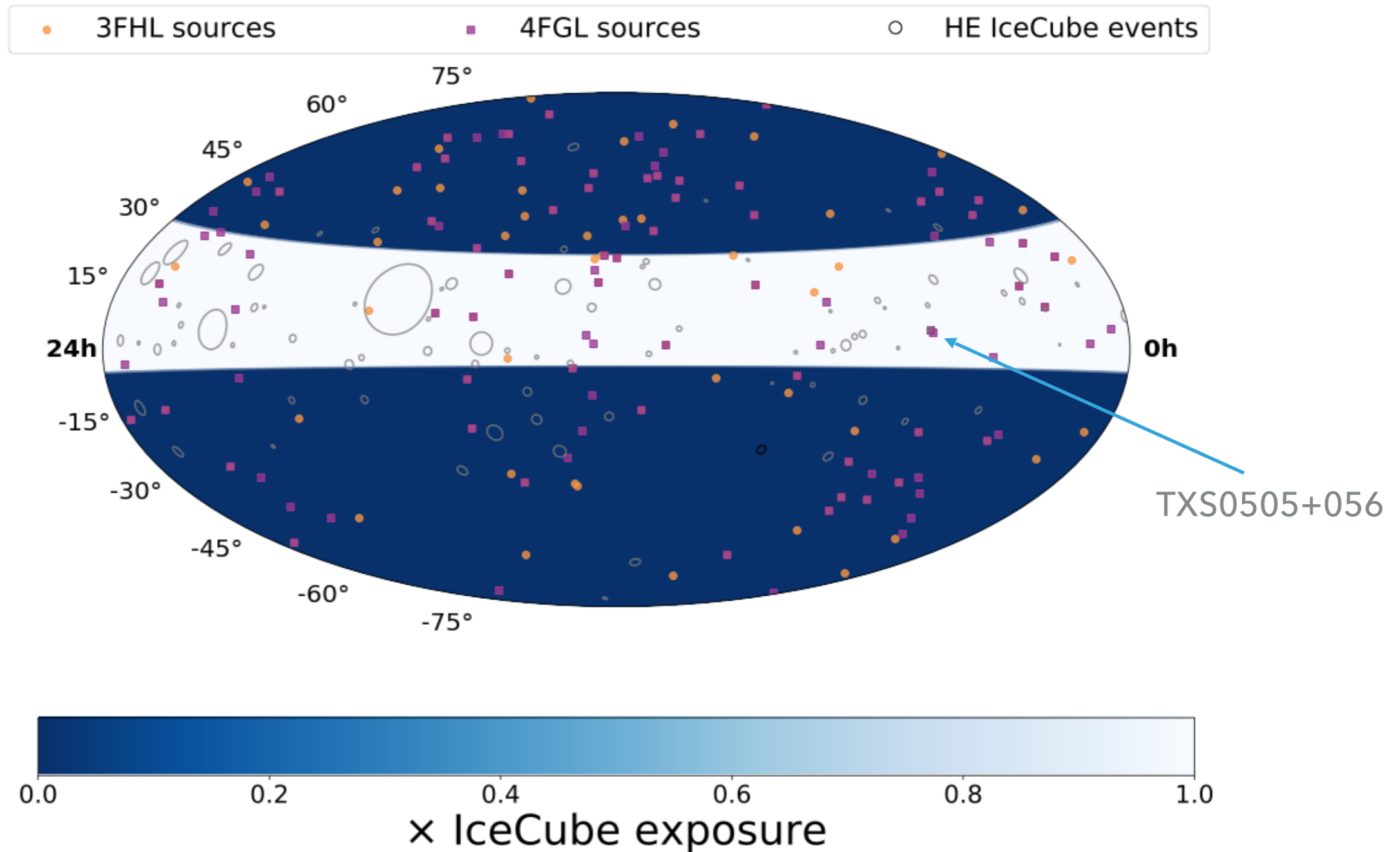
TXS0506+056 NEUTRINO CONTRIBUTION TO THE DIFFUSE: SMALL

➔ MUCH MORE TO DISCOVER OUT THERE!!



ICECUBE FIELD OF VIEW AT HIGH ENERGIES ($>50\text{TeV}$)

ABOUT 1/3 OF THE SKY COVERED

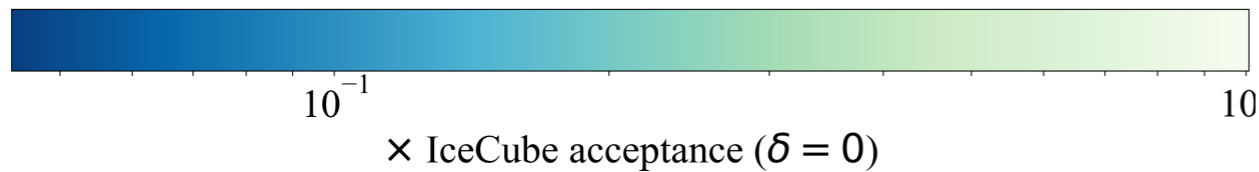
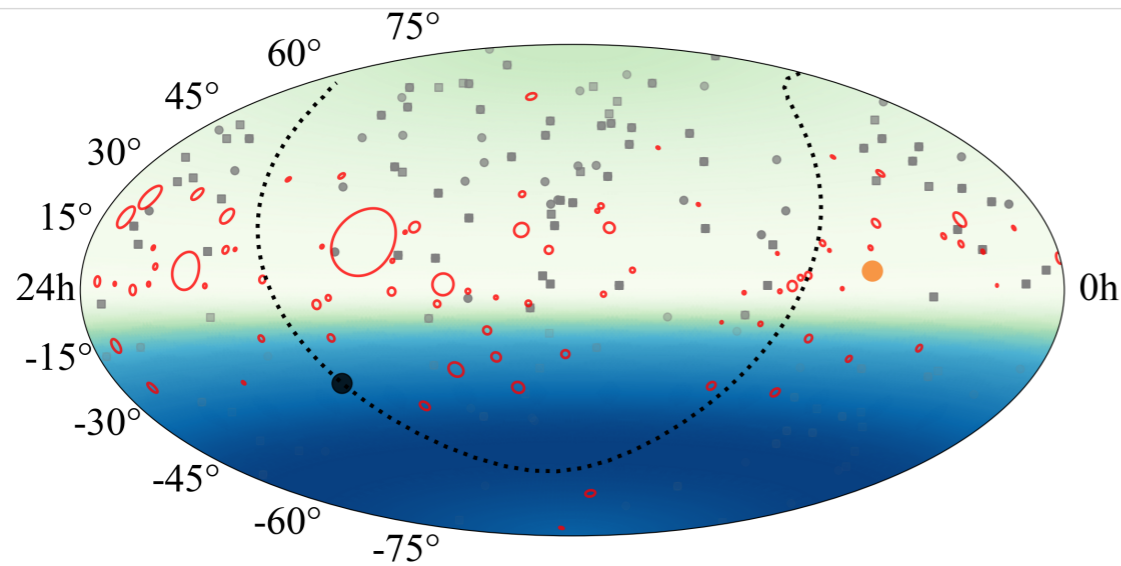


ASSUME ONE ICECUBE @ BAIKAL, @ CAPO PASSERO, @ OCEAN NETWORKS CANADA

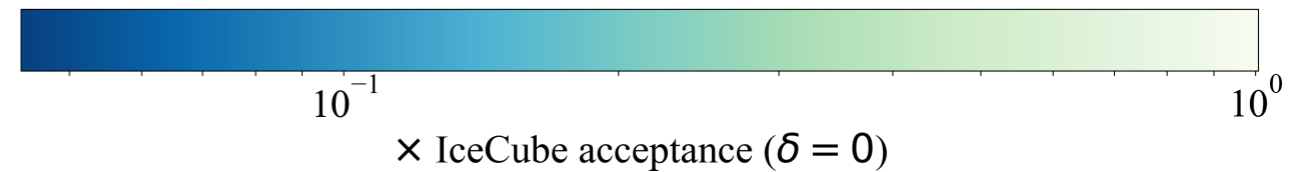
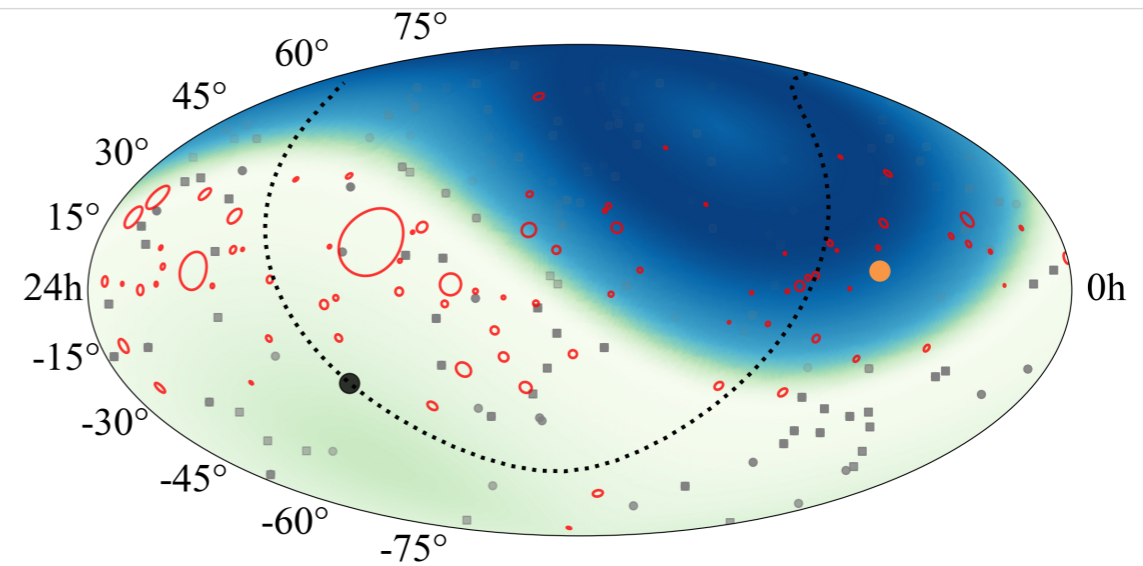
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- Galactic center/plane
- TXS 0506+056
- 3FHL sources
- 4FGL sources
- HE IceCube events
- 100 brightest sources

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$$\text{IceCube acceptance} \equiv \int_0^\infty A_{\text{eff}}(\delta, E) \cdot E^{-\gamma} dE$$

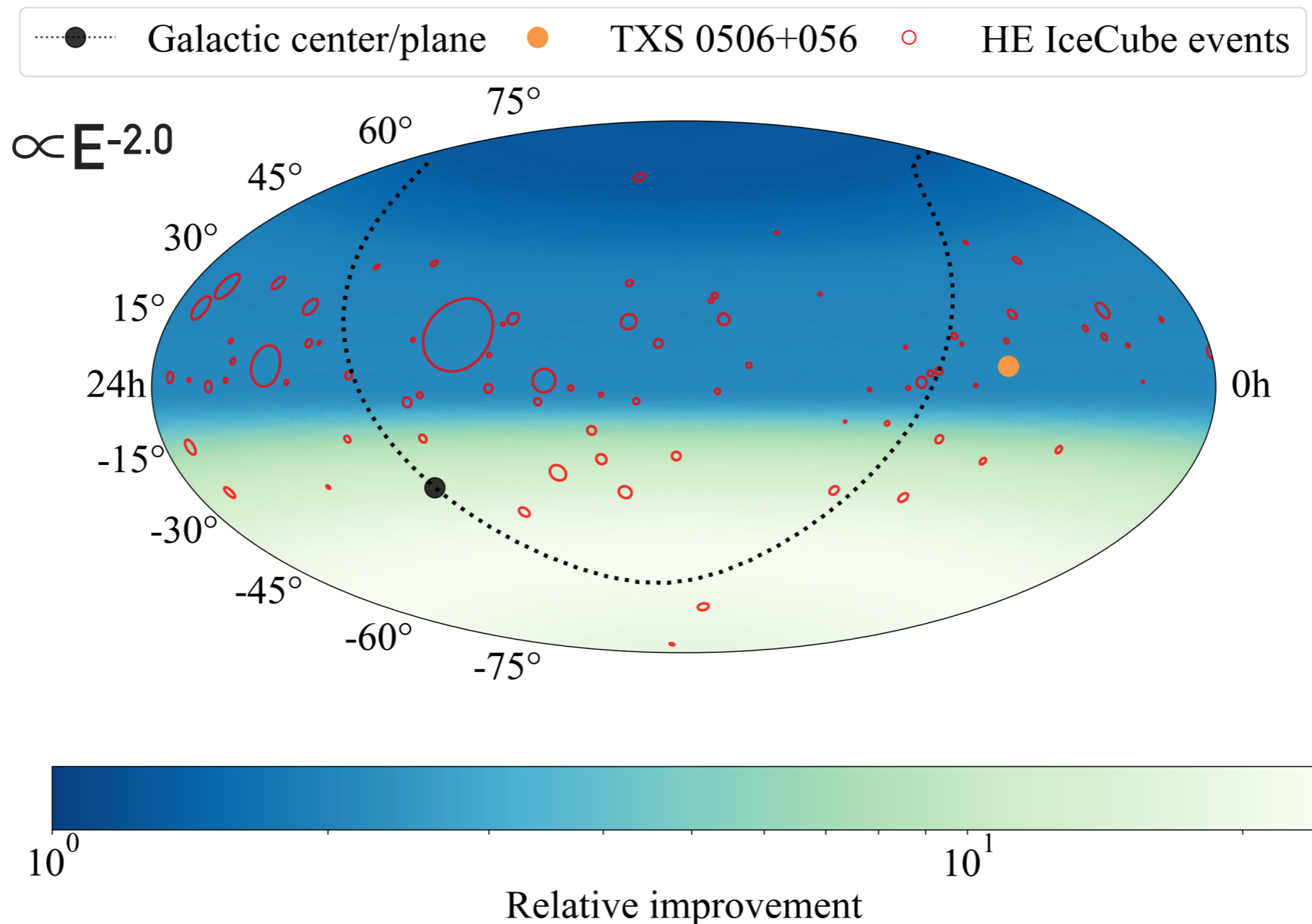


IceCube acceptance at the GVD location

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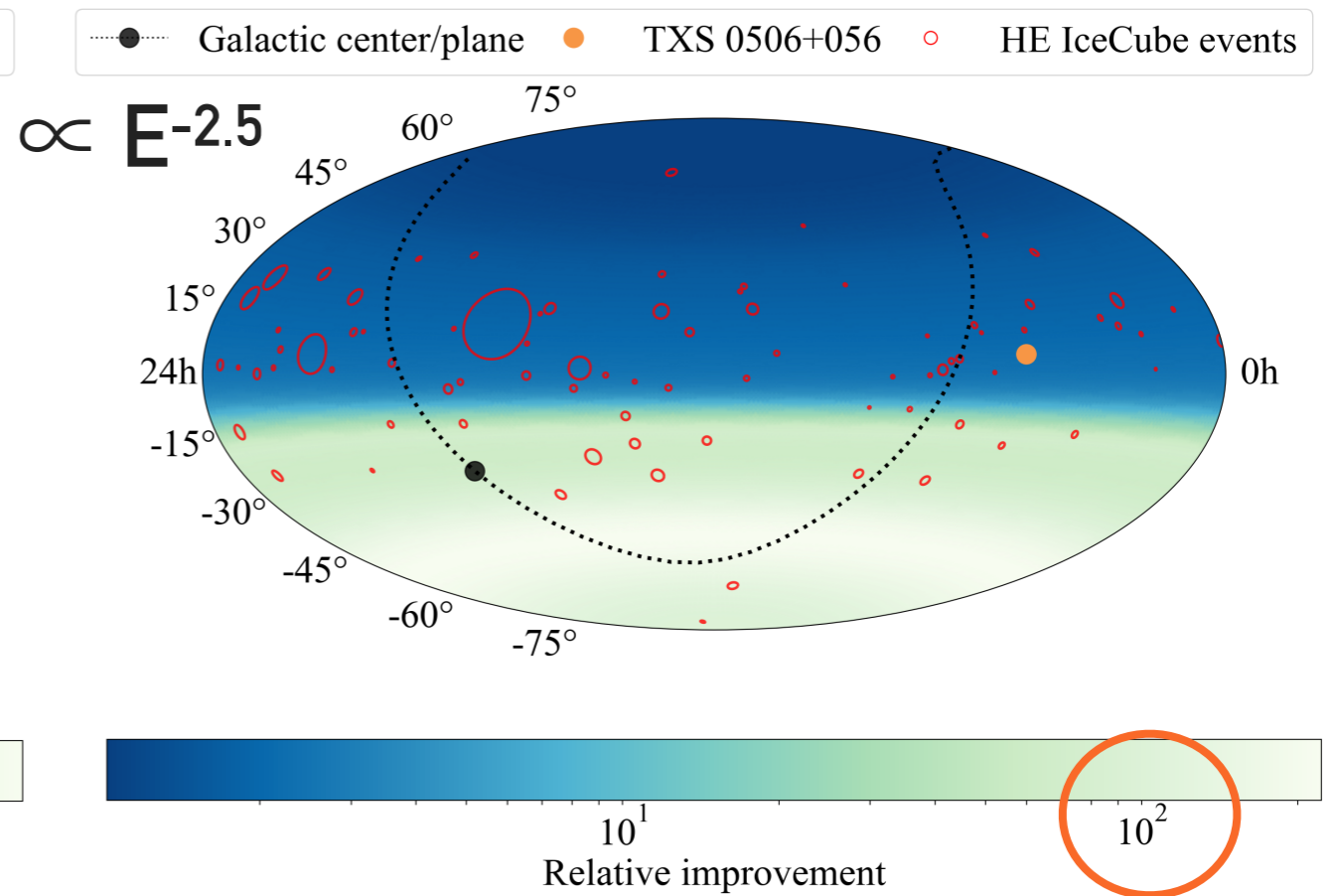
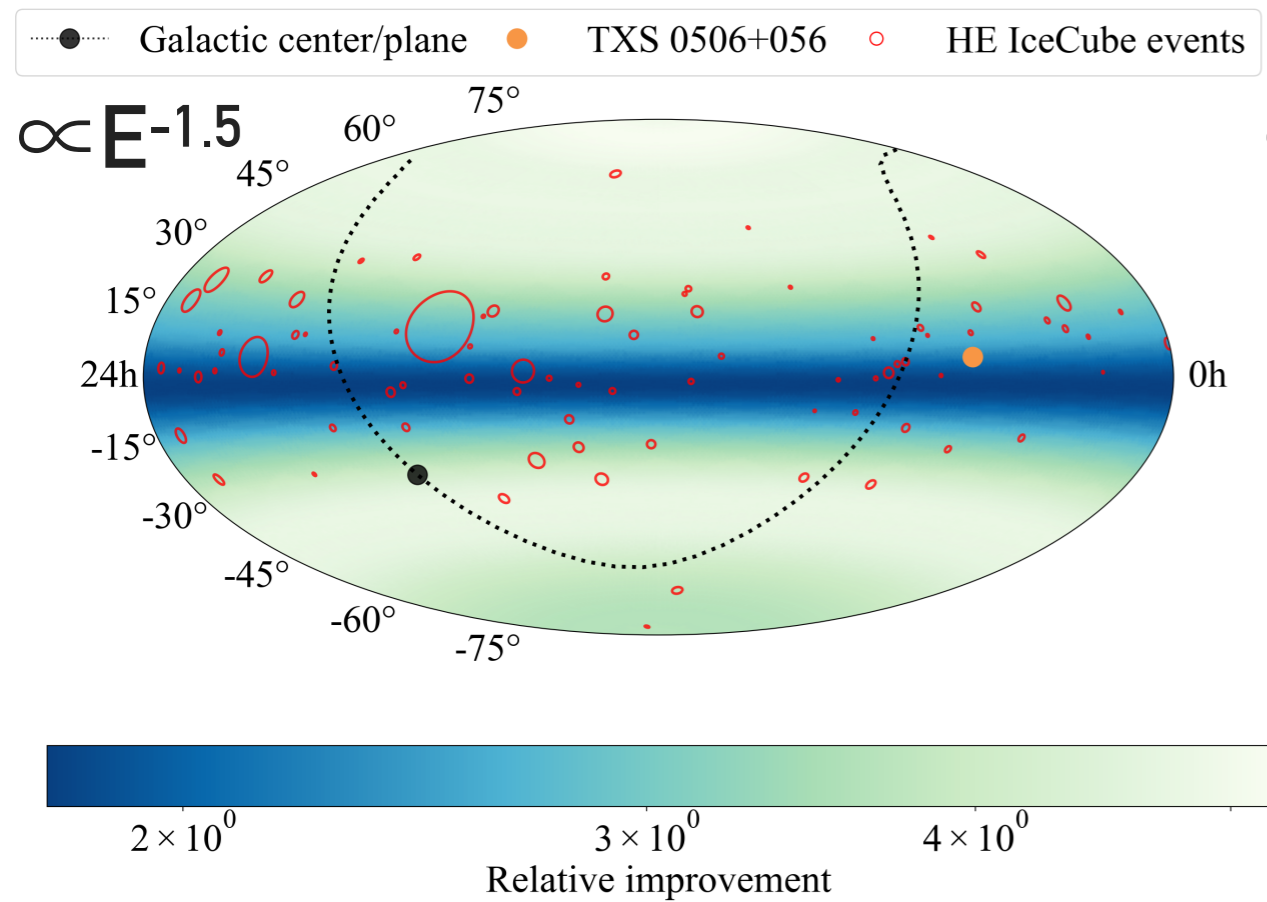
→ RELATIVE IMPROVEMENT VS ICECUBE ALL SKY



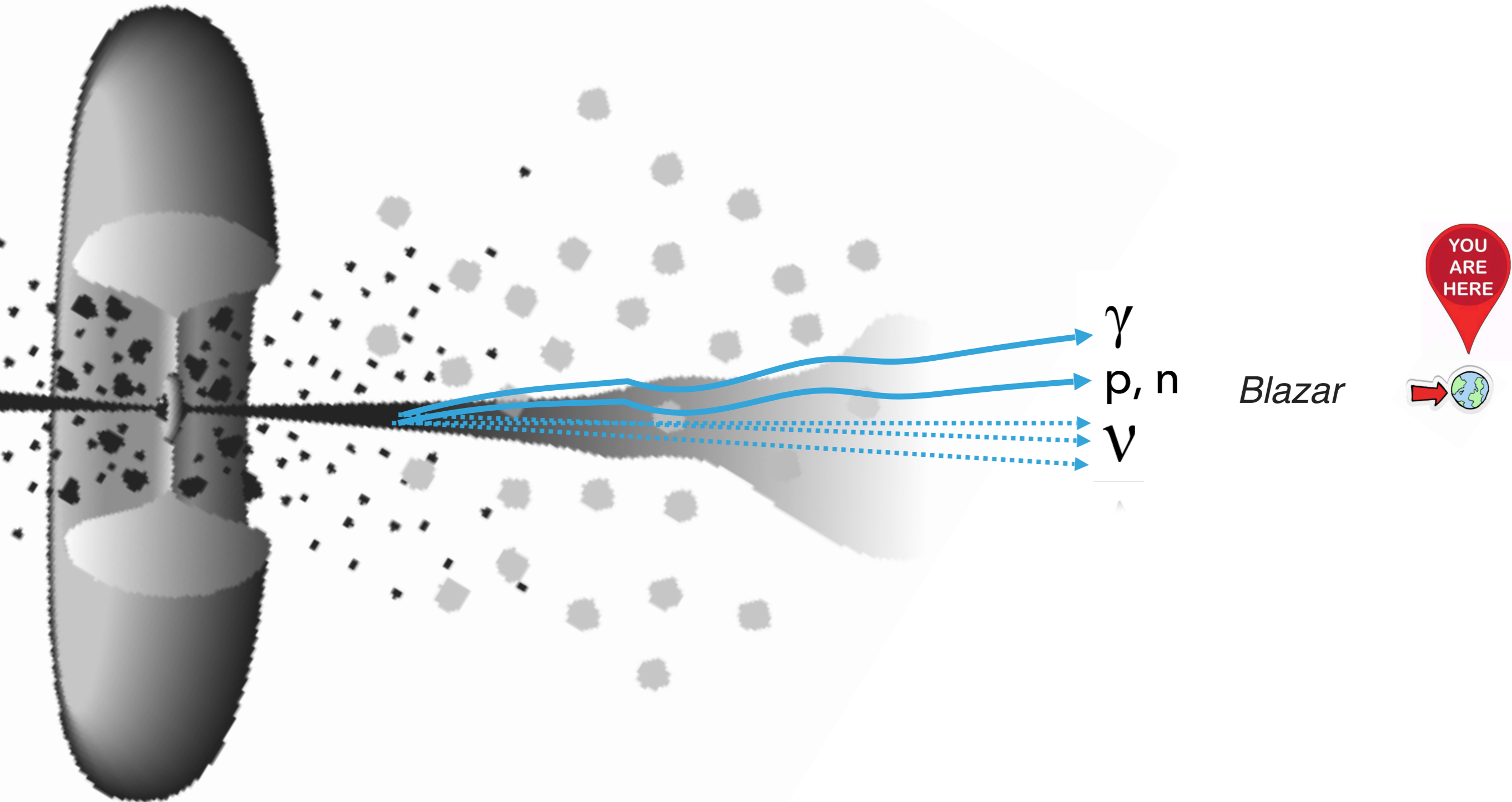
PLE_vM

ICECUBE & BAIKAL & CAPO PASSERO & OCEAN NETWORK CANADA

➔ RELATIVE IMPROVEMENT VS ICECUBE ALL SKY



WHY NEUTRINOS FOR ASTRONOMY?



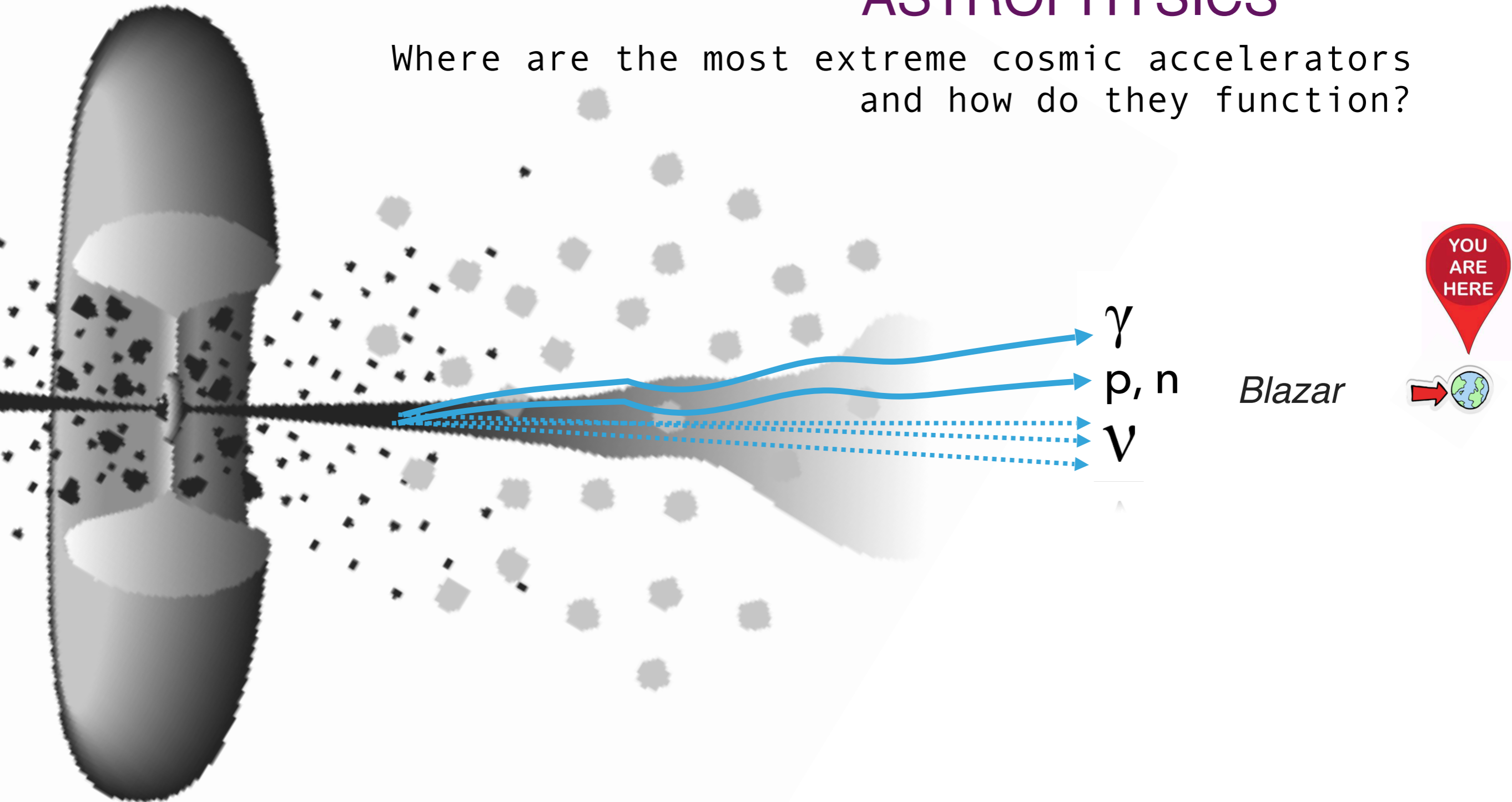
Urry, Padovani '95

[DO NOT COVER HERE THE PARTICLE PHYSICS PART RELATED TO NEUTRINO TELESCOPES]

WHY NEUTRINOS FOR ASTRONOMY?

RELATIVISTIC ASTROPHYSICS

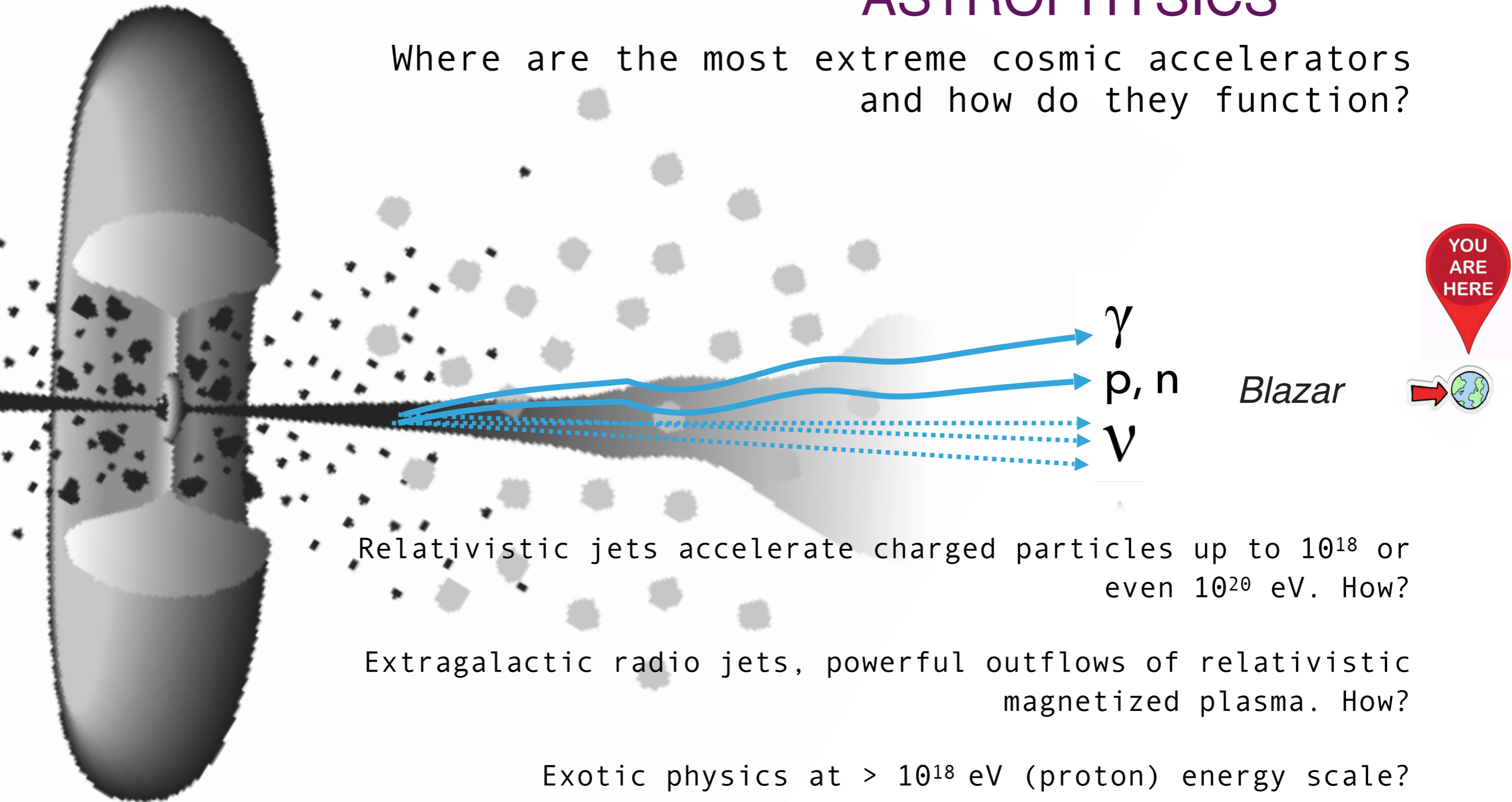
Where are the most extreme cosmic accelerators
and how do they function?



WHY NEUTRINOS FOR ASTRONOMY?

RELATIVISTIC ASTROPHYSICS

Where are the most extreme cosmic accelerators and how do they function?



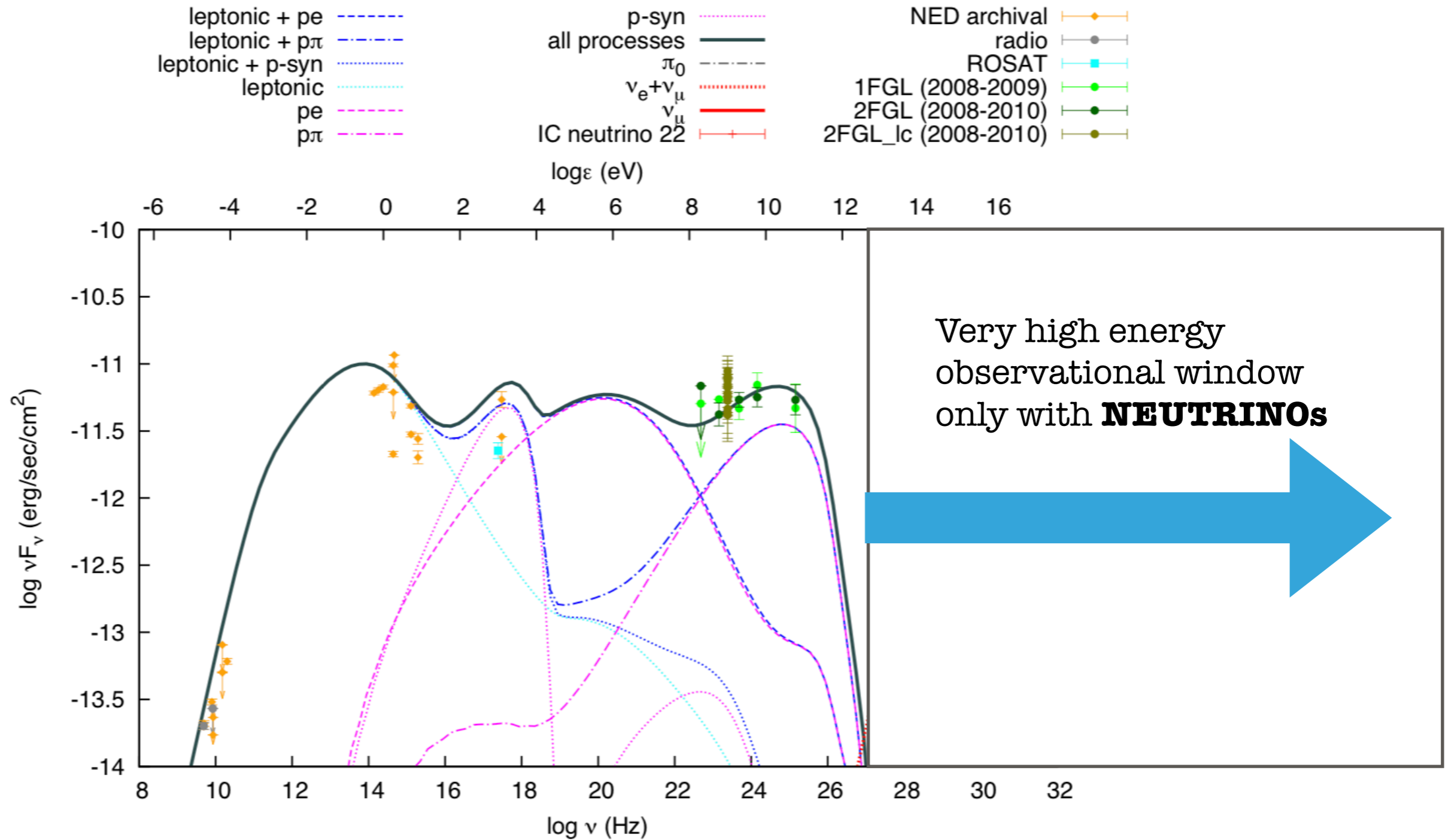
Relativistic jets accelerate charged particles up to 10^{18} or even 10^{20} eV. How?

Extragalactic radio jets, powerful outflows of relativistic magnetized plasma. How?

Exotic physics at $> 10^{18}$ eV (proton) energy scale?

WHY NEUTRINOS FOR ASTRONOMY?

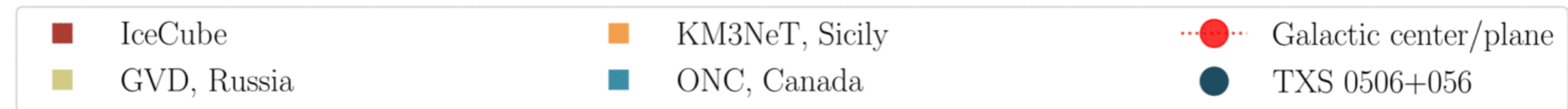
[M. Petropoulou, S. Dimitrakoudis, P. Padovani, A. Mastichiadis, *E. R.* MNRAS(2015)]



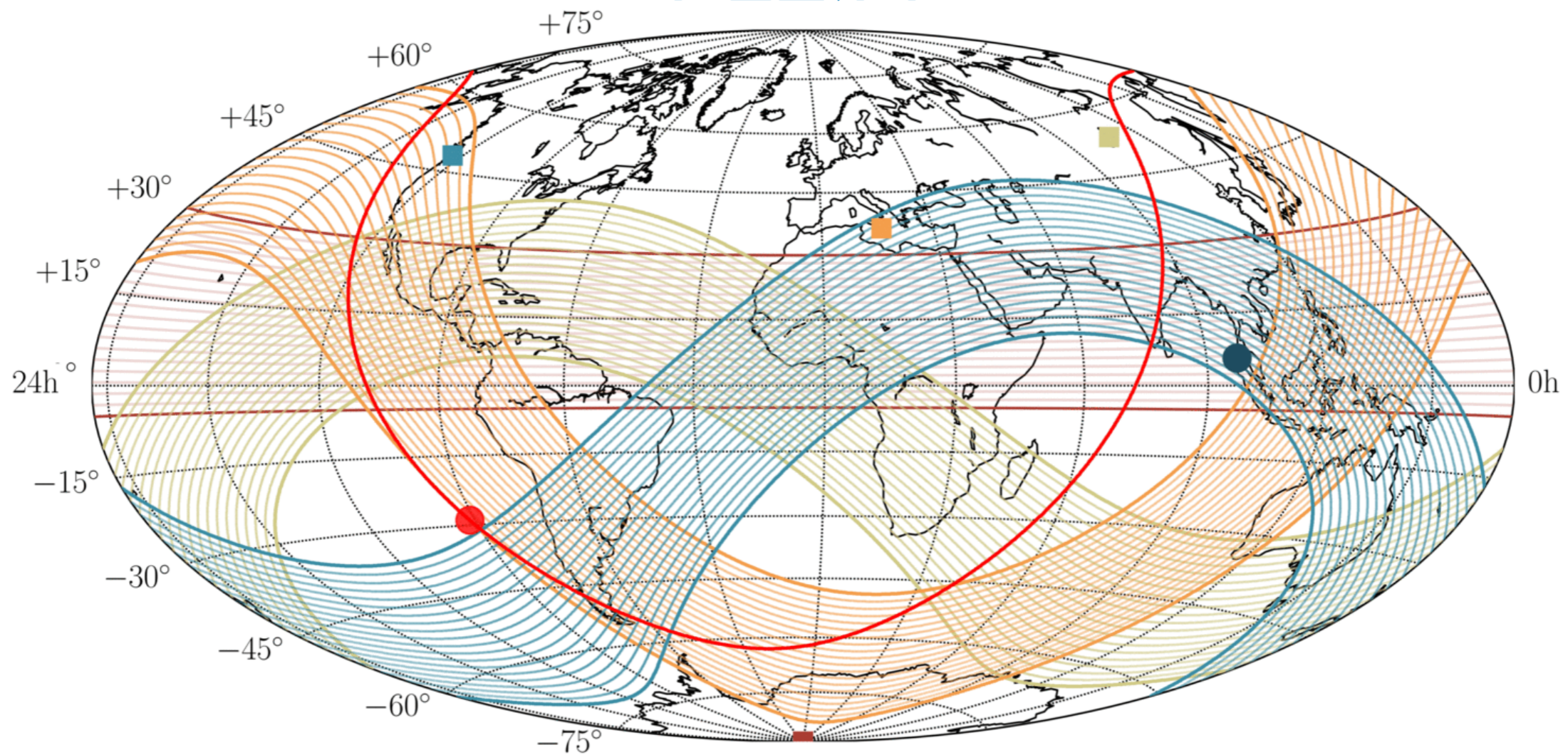
The universe is not transparent to photons >50-100TeV but it is transparent to neutrinos. [$@10\text{TeV} < 90\%$ gamma-ray photons from sources at $z \sim 0.1$]¹

¹ Dominguez, A. et al. Extragalactic background light inferred from AEGIS galaxy-SED-typefractions. MNRAS (2011)

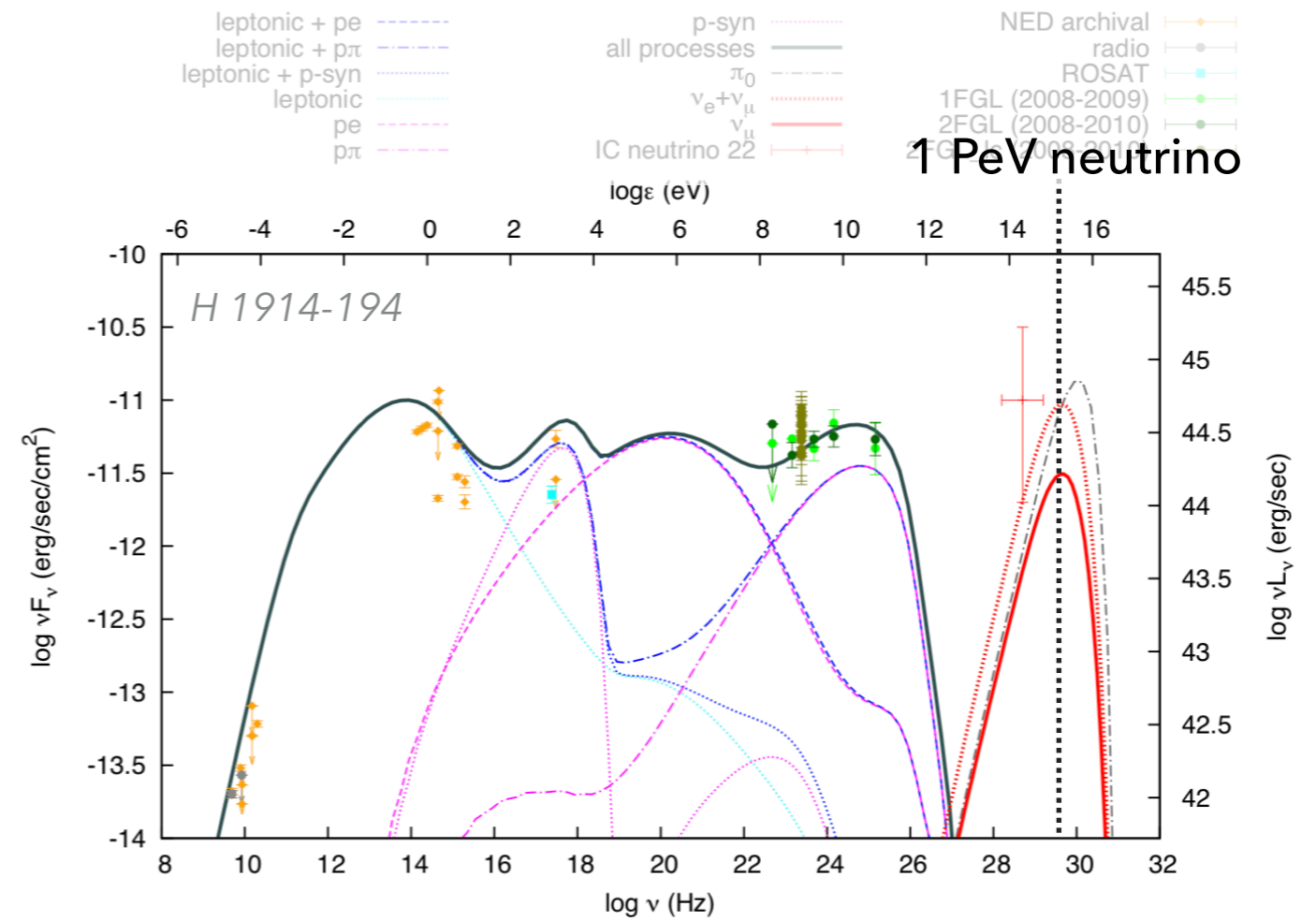
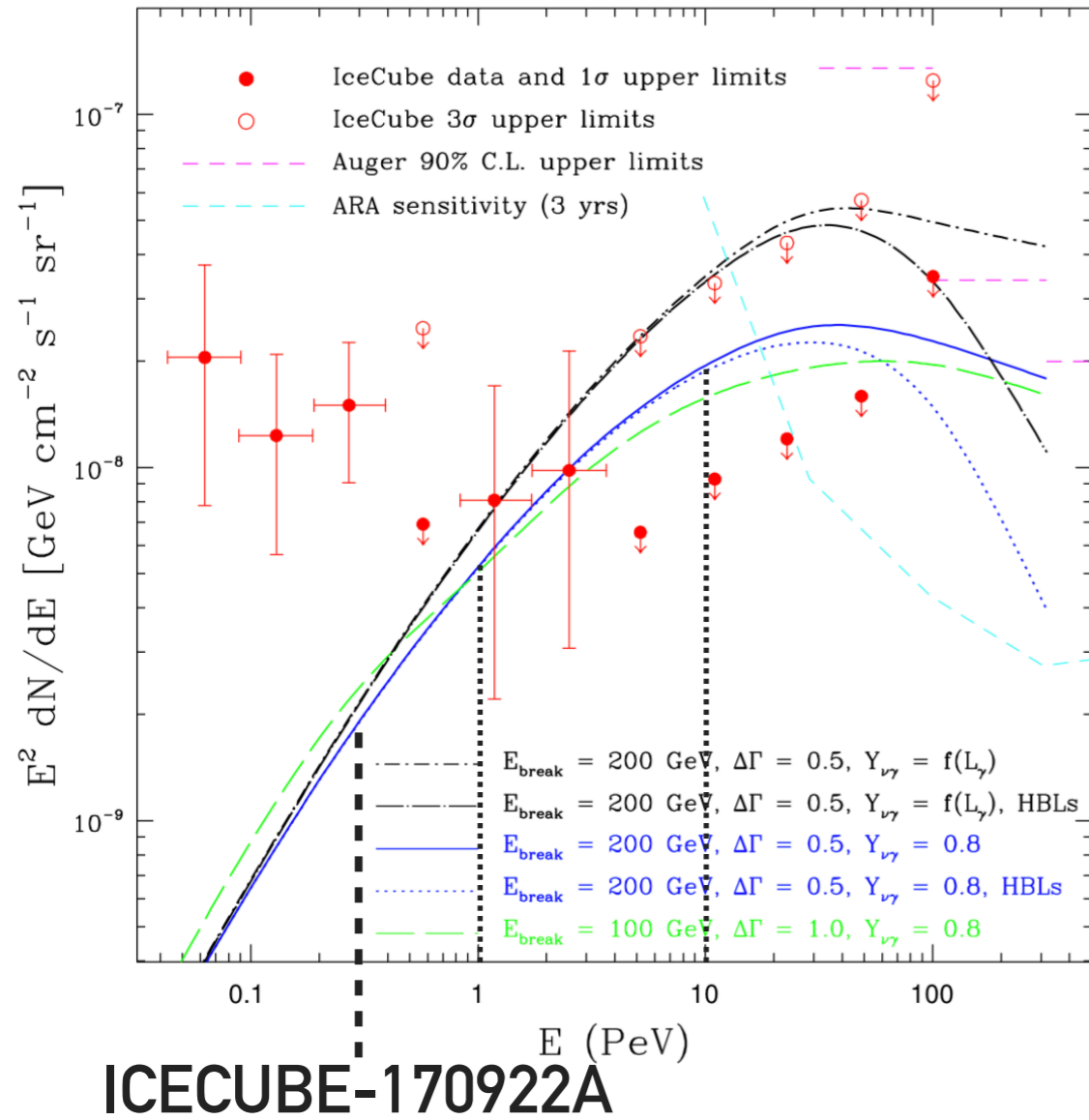
THE FRONTIER: A PLANETARY NEUTRINO MONITORING SYSTEM



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5) Hint of neutrinos from blazars anticipated prior the TXS0506+056 observation



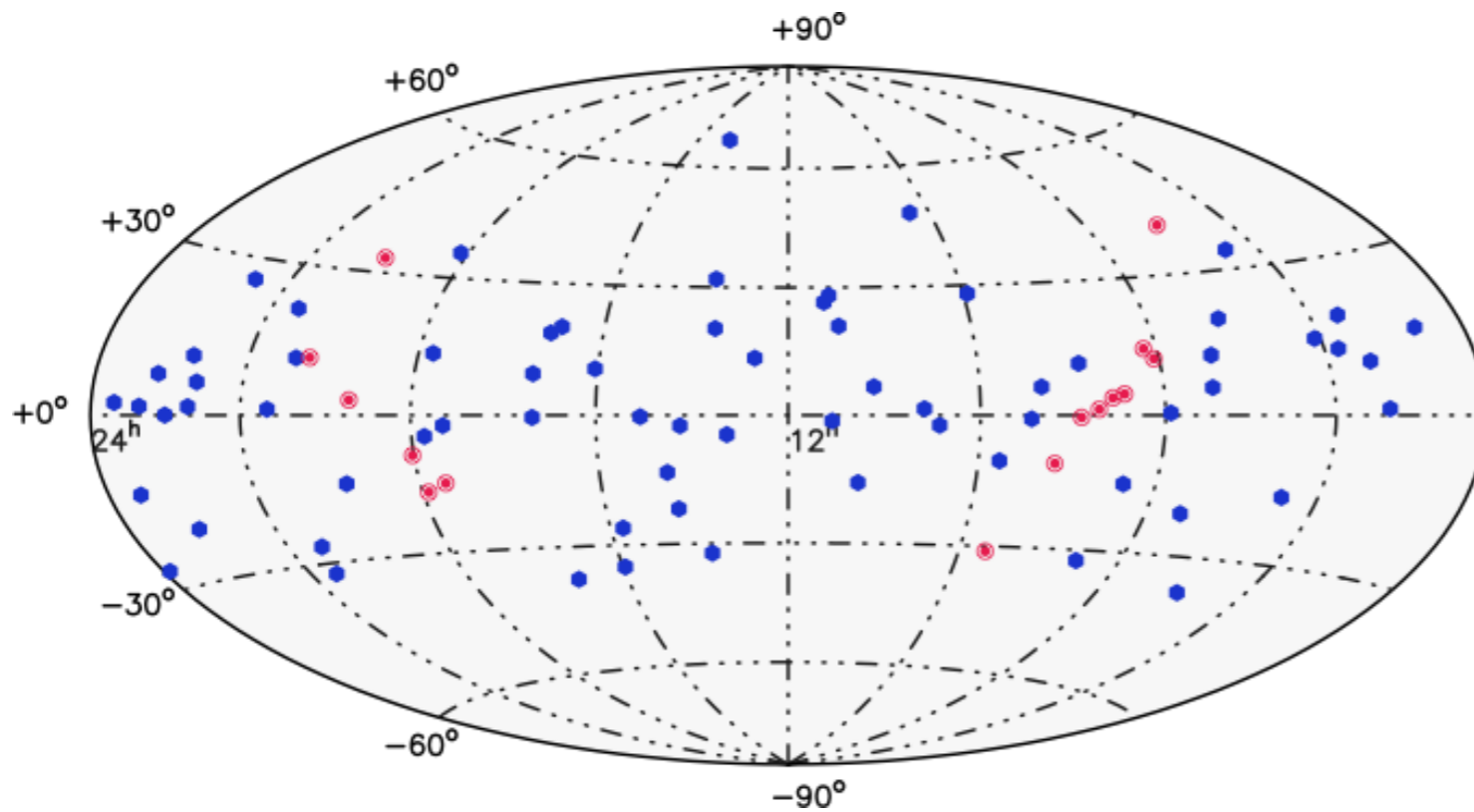
P. Padovani, M. Petropoulou, P. Giommi, E. R., MNRAS(2015)
 * P. Padovani, P. Giommi, E. R. and others, MNRAS (2019)

M. Petropoulou, S. Dimitrakoudis, P. Padovani,
 A. Mastichiadis, E. R. MNRAS(2015)

6) Evidence of neutrinos from blazars ... growing

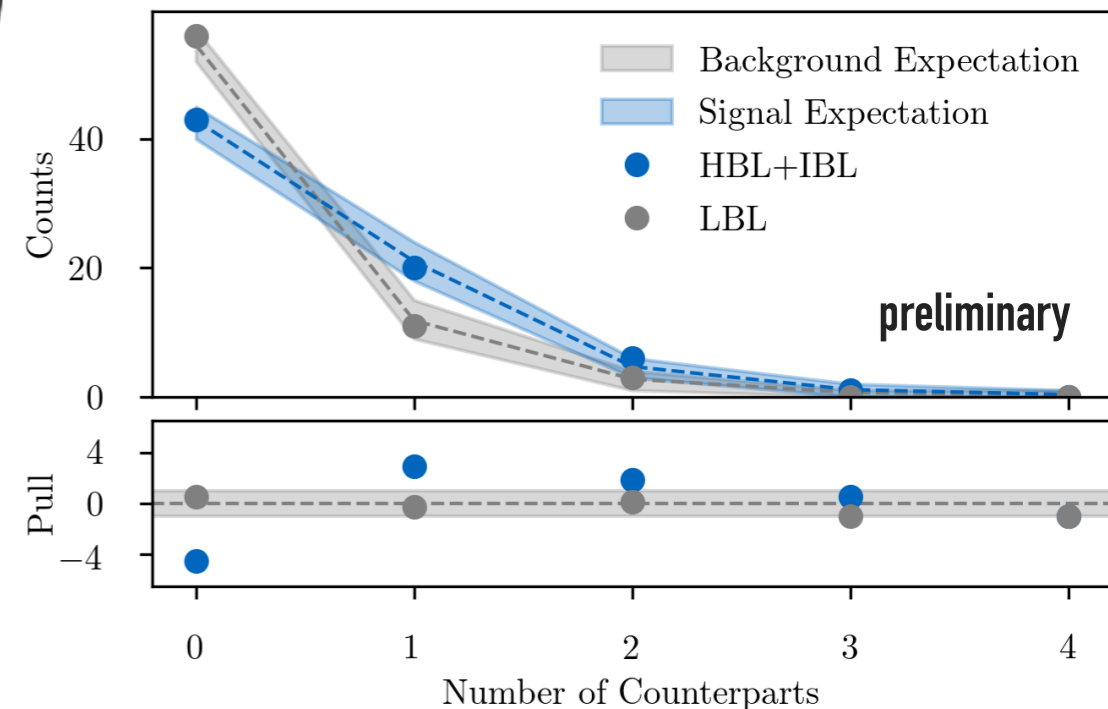
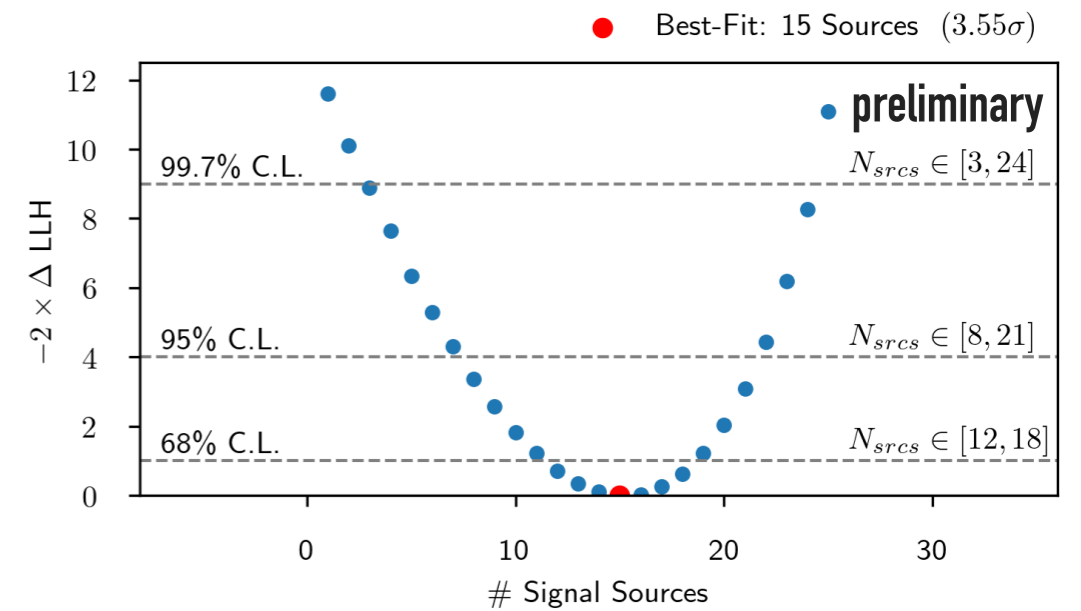
P. Giommi, T. Glauch, P. Padovani, E. R., A. Turcati, Y.L. Chang Dissecting the regions around IceCube high-energy neutrinos: growing evidence for the blazar connection, **MNRAS (2020)**

IceCube (public) high energy tracks in equatorial coordinates -



Low Galactic latitude in red (not used in the search for counterparts).

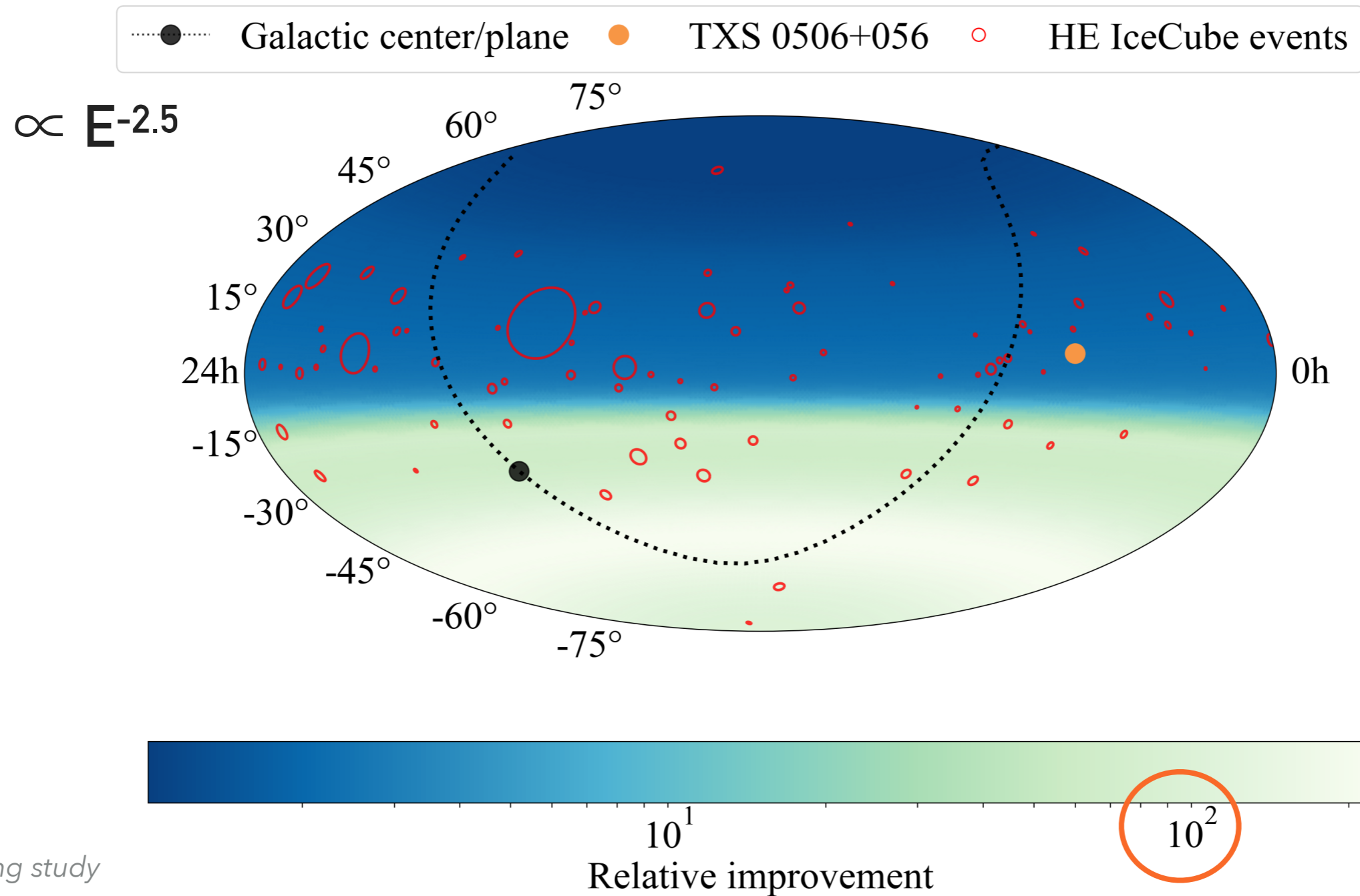
More than 70 gamma-ray emitting blazars found in spatial coincidence



PLEνM

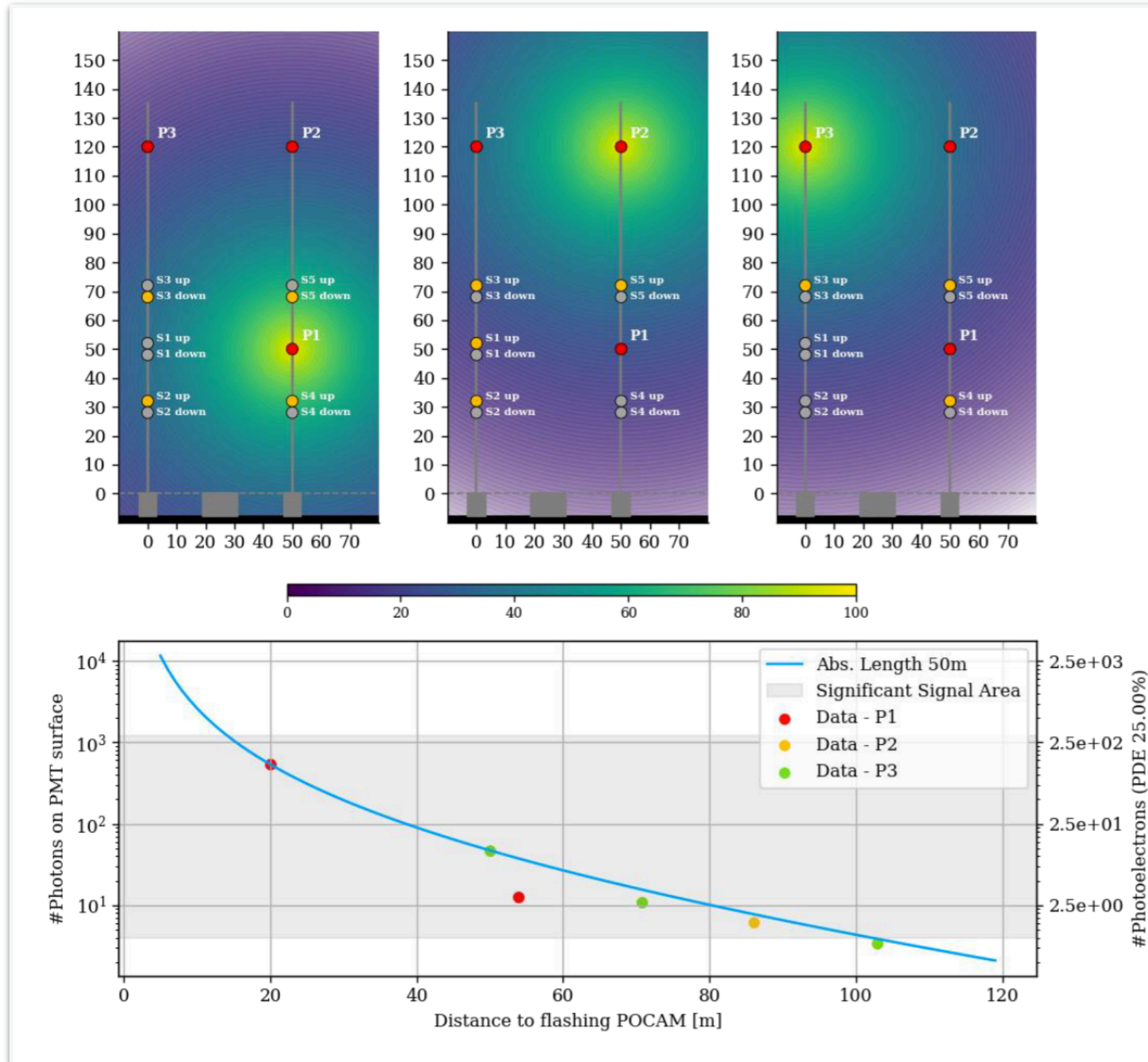
ICECUBE & BAIKAL & CAPO PASSERO & OCEAN NETWORK CANADA

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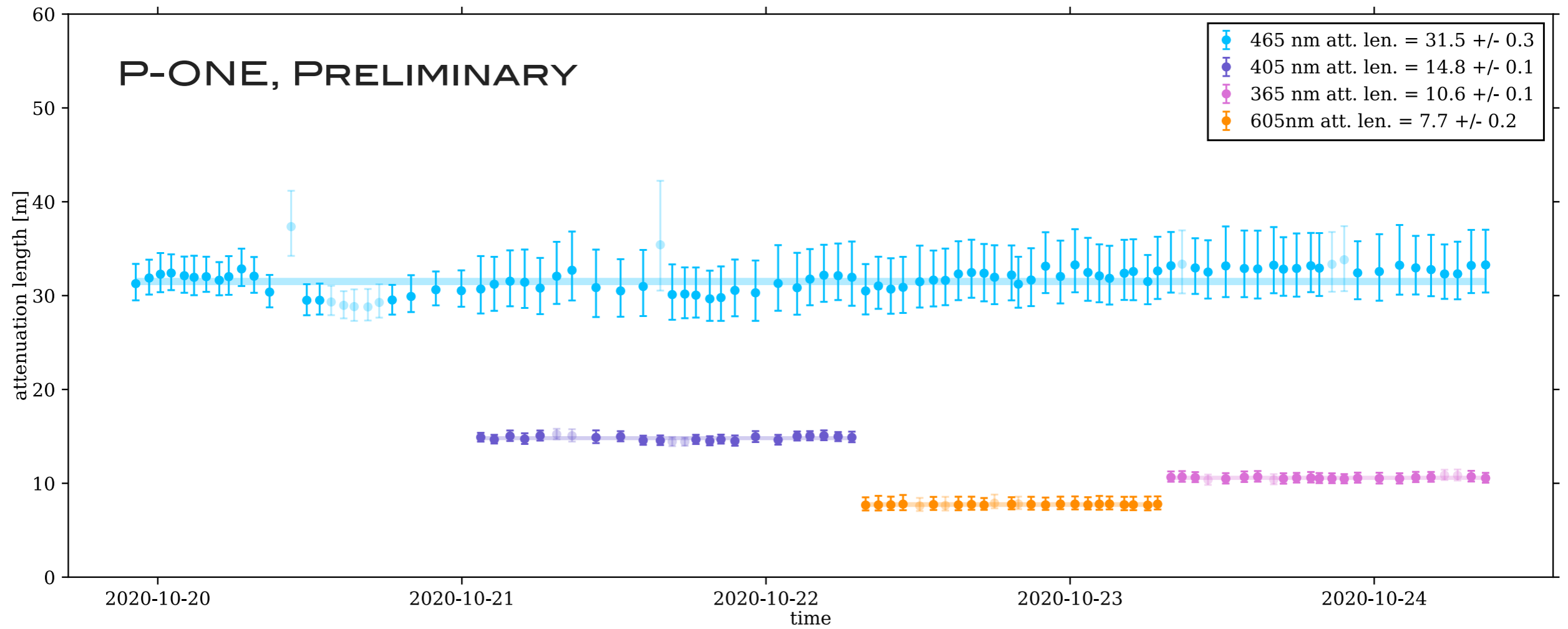


on going study

STRAW CALIBRATION



STRAW CALIBRATION



NEUTRINOS FROM THE UNIVERSE

Formaggio, Zeller, Rev. Mod. Phys. 2012, arXiv:1305.7513

modified from Vitagliano, Tamborra and Raffelt, Rev.Mod.Phys 2019, arXiv:1910.11878

